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TENSILE PROPERTIES OF ASPHALT FILMS

BY

UMANATH SHARAN

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR
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FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "TENSILE PROPERTIES OF ASPHALT FILMS" submitted by Umanath Sharan in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The object of the investigation was to study the behaviour of two asphalts in tension. These two asphalts were of the same penetration grade and used on two different sections of Highway 57A of the Province of Alberta. Although the pavement placement conditions were almost identical, the frequency of transverse cracking was very different.

Since tensile stresses induced in the asphalt pavement are resisted or relieved by the asphalt binder, the tensile stress-strain properties of the asphalts recovered from the pavements were investigated. The effect of the rate of strain, film thickness and temperatures on the asphalt specimens were studied.

Simple devices for recording the load-deformation characteristics of asphalt films were designed and fabricated.

The tests indicated that the stress-strain characteristics of the two asphalts were not the same. Asphalt used in the cracked section developed more stress for the same amount of strain than the asphalt used in the uncracked section at all temperatures. The stiffness modulus of the material from the cracked section was greater than that of the latter at all temperatures and rates of strain.

It is therefore concluded that asphalts having higher stiffness modulii are more likely to exhibit cracking in a pavement. The major recommendations are to investigate the tensile strength properties of more asphalt binders as well as asphalt mixtures of cracked and uncracked areas.

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GLOSSARY OF TERMS

Bitumen : is a mixture of hydrocarbons of natural or pyrogenous origin, or a combination of both, frequently accompanied by nonmetallic derivatives which may be gaseous, liquid, semisolid or solid and which are completely soluble in carbon disulfide.

Asphalts : are black to dark brown semisolid to solid cementitious materials consisting principally of bitumen that gradually liquefy when heated and which occur in nature as such or are obtained as a residuum in the refining of petroleum.

Asphalt Concrete : is a high quality, thoroughly controlled hot mixture of asphalt cement and well-graded, high quality aggregate, thoroughly compacted into a uniform dense mass. It is also called asphaltic concrete.

Newtonian : when the shearing stress is proportional to the rate of shear, the flow is called Newtonian.

Non-Newtonian : when the shear stress is not linear with the shear rate, the flow is called non-Newtonian.

Rheology : is the study of materials whose deformation characteristics vary not only with load but also with time rate of loading.

Viscoelastic Materials : are those which exhibit both elastic and viscous behaviour. When loaded extremely rapidly, they exhibit elastic behaviour and when loaded very slowly, viscous behaviour.

Thermoplastic Materials : are those whose consistency or degree of hardness varies with temperature.

Hardening : is the increase in viscosity.

Optimum Temperature : the temperature at which the tensile strength is maximum.

Optimum Film Thickness : the film thickness at which the tensile strength is maximum.

Stiffness Modulus : is the ratio of the tensile strength to tensile strain and its values are dependent upon the time of loading and temperature.

Microaggregate : are aggregate particles smaller than 100 microns which cannot be seen by unaided eye.

CHAPTER I

INTRODUCTION

1.1 General

The occurrence of cracking has been very commonly observed on many highways of the Province of Alberta after one or two years of service. They appear as a network of linear transverse cracks in association with longitudinal cracks along the center line and shoulders, in many instances resulting in loss of performance and expected life. The maintenance of these cracks alone involves considerable expenditure. Therefore, a detailed investigation regarding the causes of these cracks has been undertaken by the Alberta Joint Highway Research Programme. This thesis is a contribution to this programme.

A crack is a manifestation of a pavement failure in tension and may be influenced by a variety of factors such as the properties of the surfacing, subgrade, traffic and climatic conditions. An analysis of these factors may lead to the better understanding of the cracking problem.

A surfacing consists of bitumen and mineral aggregates, therefore, its properties will depend upon that of the components. A crack may develop in surfacing due to inadequate or loss of adhesion between bitumen and mineral aggregate, cohesive strength of the bitumen or tensile strength of aggregates.

The subgrade soil may contribute to cracking in a number of ways depending upon its properties. The swelling of the subsoil due to the

percolation of surface water to subgrade may cause surface warping and further cracks. It is also postulated that closed system freezing of the plastic sub-soil may result in net volume changes (shrinkage) of the magnitude considerably greater than simple unrestricted thermal contraction for asphaltic concrete. Freezing shrinkage of the subgrade soil may induce pre-stressed zones of tension and compression alternately. A rapid warming at the surface may result in further loss of strength and consequent rupture.

It is further postulated by some that the shrinkage phenomena due to certain environmental conditions may produce uniform and regular transverse cracking patterns within the homogeneous pavement sections. They have considered linear contraction of an elemental width of asphaltic concrete supported on an unyielding medium. As the surface tends to contract from a free boundary, the non-yielding supporting medium tends to restrain this movement through horizontal shear stress at the interface which may result in the formation of a crack.

The traffic may also induce tensile, compressive and shear stresses in a pavement. However, it is generally established that the presence of the transverse cracks in pavements recently studied, are caused by the factors other than the traffic (Shields, 1964).

In order to study the problem of cracking, all the above factors will have to be studied, selecting one at a time. Since cracking is a sign of failure in tension and asphalt provides the cohesive or tensile strength, the analysis of the tensile properties of asphalt seems warranted.

1.2 Purpose and Scope of this Investigation

The prime object of this investigation was to compare and analyse the fundamental tensile strength properties of two asphalts of the same penetration grade but which have shown widely different behaviour in the field. These asphalts were used on two different sections of the Highway No. 57A of the Province of Alberta, located approximately sixty miles west of Edmonton. One of the sections has developed 348 cracks per mile whereas the other has developed none, although the placement and environmental conditions were practically the same.

As stated earlier, this investigation is a part of a continuing series of investigations on the cracking of asphalt concrete pavement under study by the Joint Highway Research Program in Alberta. The initial investigations within this program were directed to a survey of high, moderate and low transverse cracking areas, recovery of large diameter cores of the asphalt concrete surfaces of the above areas and classification measurements of base and subgrade components.

An M.Sc* thesis investigation, involving one highway project, obtained data on the mixture and recovered asphalt characteristics with particular attention to low temperature ductility and penetration tests. This data is currently being analyzed in an attempt to relate these properties with the observed degree of transverse cracking. The low temperature penetration and the temperature-viscosity characteristics of the asphalts of many more projects are being studied by the personnel of

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* M.Sc. thesis programme of A. MacRury.

the Research Council of Alberta. It was felt that the next work within this program should be concerned with evaluating and comparing the tensile strength properties of asphalts used in the cracked and uncracked sections of the pavements.

In order to obtain results as definitive as possible from the testing program, it was decided to make constant as many variables as possible. Film thickness, rate of strain and temperature were taken as variables for evaluation and comparison of the tensile strength of the two asphalts.

There are many limitations to this thesis. It includes the investigation of only two types of asphalts and many other variables such as viscosity, type and shape of adhering surface has not been considered. Only the strength of the asphalt film, coated on a polished steel surface has been studied. Any failure due to lack of adhesion has also not been considered. Thus it gives only a part of the information about the cracking phenomena in pavement, i.e. the cracking occurring due to the rupture of the asphalt films. Cracking in pavement may also occur due to lack of adhesion between the asphalt aggregate interface or rupture of the aggregate. An investigation, within a broad program, may be carried out to include the effect of all the above factors. It may provide an important and necessary link between the understanding of the technology of asphalt and eventual rational method of design of a bituminous pavement.

1.3 Organization of the Thesis

The thesis proper starts with a review of literature on tension tests of asphalt concrete and asphalt films. It attempts to explain the

results of all the tension tests performed so far, in order to find the fundamental strength properties of asphalt in thin films. Several other discussions are contained in this chapter, particularly those referring to the factors affecting the tensile strength and the stiffness of asphalts, the reason being that these particular topics are especially important to the interpretation and discussion of the test results.

The third chapter describes the two asphalts used in the investigation and the physical properties of the subgrade and base-course materials.

CHAPTER IV contains a brief outline of the testing procedure and testing program.

CHAPTER V is devoted to the presentation of the test results. The plots of the various strengths and other significant relationships are summarized on common plots to facilitate comparisons.

The sixth chapter contains fairly detailed analysis and discussion of test results. It is intended in this chapter to show the fundamental difference between the two asphalts as regards the tensile strength properties.

CHAPTER VII gives a brief summary of the conclusions and recommendations following from the test results and pertinent literature review. This chapter is followed by a section on List of References.

The Appendices contain detailed reviews of the theories for tensile strength of asphalt films, description and calibration of testing equipment, sources of errors and sample calculations and sample data sheets.

CHAPTER II

REVIEW OF TENSION TESTS ON BITUMINOUS MATERIALS

2.1 General

The development of a pavement design procedure based upon fundamental considerations has been emphasized particularly during the last decade. A road structure may be considered to be made up of a series of elastic layers lying on a semi-infinite elastic mass. Stresses, strains and deflection of such a structure under critical conditions of loading serve as a criterion for design. Stress and strain can be calculated, however, only if the elastic properties of the materials in each layer are known.

Peattie (1962) suggests that the effects of the fatigue due to the cumulative action of repetitive traffic loads and the occasional very heavy vehicle, must also be taken into account in pavement design. In case of fatigue, the horizontal tensile strain is considered as critical whereas in the case of occasional heavy loads, it is the horizontal tensile stress.

Asphalt is called a thermoplastic material since its consistency or degree of hardness varies with the temperature. It is also called a viscoelastic material as its stress-strain characteristics are dependent upon the rate of loading. Under slow rate of loading, it behaves as a viscous material and under fast rate, as an elastic material.

The tensile properties of asphalt and especially of asphaltic concrete have been investigated to a very limited extent. The correlation of these properties with the field performance was done by Dorman and Jarman (1958) using the concept of stiffness which was introduced by Van der Poel (1954) to describe the viscoelastic behaviour of the asphalts. The effect of the practical stress condition on relative stiffness of a 100-penetration bitumen and the resultant possible defects in a pavement, will be discussed in more detail later on in this Chapter.

In the following paragraphs an attempt is made to review the results of tests on asphalt concrete and asphalt to determine the mechanism of behaviour of asphalt in pure tension. It is further intended to extend certain of these concepts to the particular investigation of this thesis and propose new ones in an effort to advance fundamental knowledge.

2.2 Tension Tests on Asphalt Concrete

There is very little information available on the tension testing of asphalt concrete. Some authors have mentioned the tensile properties of the asphalt concrete but to a very limited extent as a part of their investigations.

Alexander and his associates (1954) performed tests on 4 inch by 2 inch by 2 inch dense graded asphaltic concrete with various types of blended mix and at fast and slow rates of test. They found the strength in the range of 168 psi to 274 psi at a strain rate of 0.143 in/min which they referred to as the fast rate and of 53 psi at slow rate. The asphalt properties were, however, not reported. This was a part of their investigation of the reflection cracking in bituminous resurfacing over old cement

concrete pavements.

Nijboer (1954) performed tests with sheet asphalt specimens using 50/60 penetration asphalt but did not report his testing procedure. However, his results show that the tensile strength increases with the decrease of temperature and time of loading.

Harzett and Johnson (1961) made studies on the strength properties of bituminous concrete tested in tension and compression. The tensile strength, at a strain rate of 0.12 inch per minute, of 4 inch diameter by 4 inch samples made with a dense graded mixture and various asphalt contents were determined. The tests were done at room temperature and the tensile strength found to be in the order of 30 to 40 psi. They suggested on the basis of their tests that tensile strength, compressive strength and elastic or stress-strain characteristics are very important for establishing a design procedure for present and future highways.

A significant contribution towards the understanding of the tensile properties is that of Tons and Krokosky (1963). They studied the tensile properties of dense graded bituminous concrete at various temperatures and rates of extension with various micro-aggregate fillers. Their findings may be summarized as follows:

1) The rate of extension has less effect on the tensile strength at lower temperatures than at higher temperatures. The stress-strain curves at various temperatures seem to converge as the temperature decreases.
2) The tensile strength of the mixes increased with the decrease of temperature and was maximum around 20°F. Below 20°F, the strength started to fall off with decrease in temperature.

and 3) The total strain to failure at low temperatures for a well packed aggregate was lower even for what were described as fat mixes. They explained this as an adhesive failure between two particles at the point of contact where the films were very thin and brittle and flow of surrounding asphalt was restricted by the close packing of mineral aggregates. However, in cases of loosely packed mixes, the strain to failure was higher as the fine asphalt could easily flow from the surrounding mass. Thus two types of failure in an asphaltic concrete were indicated:
i) brittle failure when the film thickness is small and temperature low and ii) viscous failure when the film is thicker and temperature higher.

Domaschuk and his associates (1964) recently reported their work on tension testing of 10 inch by 4 inch by 2-1/2 inch specimens obtained from a pavement. The rates of strain were .008 and .0008 inch per minute and test temperatures +24°F, -4°F and 15°F. They found that for a given rate of loading, the tensile strength increases as the temperature decreases and the strain at failure increases as the temperature increases. Also at a given temperature, the tensile strength of asphaltic concrete increases with the rate of load application.

The above studies serve as a basis for the qualitative analysis of the tensile properties of asphaltic concrete. It may be said that the tensile strength of an asphalt concrete is a function of temperature, rate of loading, type of mineral aggregate and asphalt content. Faster rate of loading and lower temperature yield higher strength values but lower strain

to failure. However, the existence of an optimum temperature in the neighborhood of 20°F, as found by Tons and Krokosky, needs further study. Further studies are also needed regarding the effect of the type of mineral aggregate and asphalt content on tensile strength.

2.3 Tension Tests on Asphalt Films

There are extensive literature references on the subject of the behaviour of adhesives and other materials in thin films subjected to tensile stresses. Newtonian liquids (Reynolds, 1886) as well as non-Newtonian both have been investigated by different authors. It was found that the tensile strength of thin films of both liquid types increased as their film thickness was decreased to certain optimum values. Tests on adhesives also confirm the existence of above relationship.

In the field of asphalt, the pioneering work was done by C. Mack (1957). He used steel plates with asphalt sandwiched in between and pulled in pure tension at 77°F, with a rate of loading of 5 pounds per second or rate of strain of 10^{-6} in/sec or less. It was found that the tensile strength of asphalt when plotted on logarithmic scales increases linearly to a maximum and then decreases as the film thickness continually decreases. On an arithmetic scale this relationship would be in the form of a curve levelling off as the film thickness increases. Mack's theoretical and experimental analysis also indicate that the deformation to failure is constant for a given asphalt. He also found that the rate of loading had no effect on film strength as long as the minimum time of load application was 100 seconds. Mack's theoretical analysis is dealt with in detail in Appendix A.

P.R. Wood (1960) worked with a sliding plate microviscometer for the analysis of properties of asphalt in thin films, 10 to 100 microns thick. He also found that the tensile strength decreases as the film thickness increases and then eventually levels off with little change in tensile strength at a film thickness of 200 microns. His important finding is that the viscoelastic properties of asphalt are dependent upon the film thickness and viscosity under both shear and tensile stresses. It was generally considered before that film thickness had no influence on the viscoelastic properties of asphalt.

A recent and fairly extensive investigation of the asphalt properties in pure tension was done by Kamran Majidzadeh and Moreland Herrin (1964). Their findings also confirm that with the decrease of film thickness, the strength in tension increases and that the deformation to failure is a constant quantity at 77°F as indicated by Mack (1957). Their investigations were limited to 10 to 1000 microns film thickness, 32°F to 113°F temperatures and 1 in/min to .004 in/min rates of extension. They found principally two types of failures, viz., brittle fracture and fracture by flow and necking, the former occurring in very thin films and the latter in thicker films. The film strengths for the types of failure were dependent upon the temperature and rate of extension.

From the above investigations, it may be established that the tensile strength of an asphalt film is a function of rate of strain, temperature and film thickness. Increase of rate of strain and decrease of temperature and film thickness to a certain extent may give higher tensile strength. Also, the total strain to failure at 77°F is constant for a given asphalt.

One of the controversial points in the above investigations is the existence of an optimum film thickness in the neighbourhood of 25 to 50 microns as found by Mack (1957) where the tensile strength is maximum. P.R. Wood or Majdzadeh and Herrin have not found this in their investigations. The theoretical explanation for the optimum film thickness as suggested by Mack is based upon the energy requirement for breaking the bonds between asphalt molecules. It varies with the asphalt type, viscosity and temperature. However, working with adhesives, Koehn (1954) did find an optimum film thickness in the neighbourhood of 10 microns. But he explained this as the lack of uniformity of the films due to presence of gaps or voids in the films or the metal to metal contact at high points of surface which result in the reduction of contact area. A study of this controversial aspect of the film thickness-strength relationship appears warranted.

2.4 Factors Affecting the Tensile Strength of Asphalt Films

The factors affecting the tensile strength of thin asphalt films may be categorized into two groups:

A) those pertaining to asphalt flow properties, and

B) those pertaining to test conditions

2.4.1 Flow Properties

Asphalt flow properties are affected by (i) crude source (ii) type and degree of processing (iii) age and (iv) temperature. The following extracts from Traxler (1964) very aptly describe the above factors:

"The chemical composition of an asphalt is dependent upon the

source from which it has been obtained. Chemical composition affects the colloidal structure of the asphalt and thus the flow properties. The manner and degree to which an asphalt is processed has usually a marked effect on the flow properties. Steam or vacuum distillation produces less non-Newtonian characteristics than does air blowing (Traxler, 1964). Use of by-products from solvent refining either for the production of asphalt or as a blending agent for other materials commonly reduces the amount of gel characteristics. This in turn reduces the degree of complex flow shown by the asphalt."

"All asphalts show an increase in consistency with time not caused by the loss of volatile components. The magnitude of this effect is dependent on the source of the asphalt and the method by which it was processed. The phenomena of age hardening probably is a manifestation of the colloidal nature of asphalt, since much of the increased consistency occuring with time may be destroyed by heat or mechanical working."

"Complex flow of asphalt tends to diminish as the temperature is raised. This occurs because as the temperature increases, the dispersed materials (asphaltenes) are dissolved, thereby creating a sol-type material. A non-Newtonian asphalt may tend to show Newtonian properties at higher temperature usually a few degrees above softening point."

2.4.2 Test Conditions

The test conditions include the effect of the following factors:

i) rate of loading
ii) temperature
iii) film thickness and
iv) type and roughness of adhering surface

The viscoelastic properties of asphalt depend upon the rate of loading, temperature and film thickness. At fast rates of loading, lower temperatures and very thin films, asphalt behaves as an elastic material. Surface roughness affects the average film thickness as well as the contact angle of the asphalt and metal surface and thus the resultant film strength.

2.5 Stiffness Modulus

The concept of the stiffness modulus (S) was introduced by Van der Poel (1954) to describe the viscoelastic behaviour of asphalts. It is

analogous to, but not the same as the modulus of elasticity and is applicable to such conditions of stress and deformation under which a linear relationship exists. It is defined as the ratio of tensile strength to tensile strain.

$$S \text{ (Stiffness Modulus)} = \frac{(\text{Stress})}{(\text{Strain})}$$

The stiffness modulus varies with the duration of the stress and the temperature and may be loosely called a time and temperature dependent Young's Modulus. At very short loading times, the stiffness modulus approaches the modulus of elasticity, (E).

Dorman and Jarman (1958) studied the stiffness of dense graded mixtures and found that the stiffness increased as the temperature decreased, but below about 0°F, there was practically no change. They also found that the stiffness modulus of a bituminous mixture and pure bitumen were the same.

TABLE 1, taken from their report, shows the effect of the practical stress condition on relative stiffness of a 100-penetration bitumen and the resultant possible defects in a pavement.

"This table indicates that the extremes of stiffness occur at high temperatures with long times of loading and low temperatures with short times of loading and these are most critical conditions which the bitumen is required to withstand in practice."

TABLE 1

EFFECT OF PRACTICAL STRESS CONDITIONS ON

RELATIVE STIFFNESS OF 100-PEN. BITUMEN**

Time of Loading	Condition in Practice	Possible Defects	Relative Stiffness at -10°C	25°C	50°C
1 month	Settlement	Cracking	7×10^{-3}	4×10^{-7}	3.3×10^{-9}
1 day	Standing loads	Deformation	1.7×10^{-1}	1.2×10^{-5}	1×10^{-7}
1 hour	Standing loads	Deformation	7×10^{-1}	3×10^{-4}	2×10^{-6}
0.4 sec.	Penetration test*		8×10^{2}	1	2.3×10^{-2}
10^{-1} sec.	Slow Moving Traffic Effect on carpet	(i) Fatting-up due to compaction (ii) Deformation	1.3×10^{3}	3.3	4×10^{-2}
10^{-2} sec.	Fast moving traffic Effect on carpet	(i) Fretting (ii) Cracking (iii) Progressive deformation	2.7×10^{3}	2.3×10^{1}	3.3×10^{-1}
10^{-3} sec.	Fast Moving Traffic Effect on Carpet	Fretting	4×10^{3}	1×10^{2}	2.7

** After Dorman and Jarman

* As a basis of comparison, all the stiffness values are related to that of 100-pen. bitumen under the conditions of the penetration test at 25°C. It has been shown experimentally that the penetration is related to the stiffness of 0.4 sec. loading, the value for 100-pen. bitumen at 25°C being 4 kg/cm^2 (58 lbs/in^2).

2.6 Summary

Tensile stress-strain relationships for asphalt concrete is considered to be one of the important factors for evolving and improving design of asphalt pavements. Depending upon loading conditions, either the tensile strain or stress may be considered as the critical design factor.

The tensile strength properties of an asphalt concrete depends upon the rate of loading, temperature and asphalt content. The tensile strength of an asphalt depends upon the rate of loading, temperature and film thickness. The existence of optimum temperature in an asphalt concrete and optimum film thickness in an asphalt need further studies.

The various factors affecting the tensile strength of an asphalt film may be put into two categories: i) those pertaining to flow properties and ii) those pertaining to test procedure.

The concept of stiffness modulus appears to be very useful for describing the viscoelastic properties of asphalt and asphalt concrete as well as predicting the performance of a pavement.

CHAPTER III

MATERIALS

3.1 General

Field and laboratory data from various selected sections exhibiting transverse cracks as well as from uncracked sections have been collected by the Highways Division of the Research Council of Alberta. These data include frequency and pattern of cracks together with characteristics of the component materials as determined by the conventional testing methods.

The asphalts selected for this investigation were taken from two sections of the Highway No. 57A, located approximately sixty miles west of Edmonton. One section had a frequency of 348 cracks per mile but an adjacent section had none. For convenience, the asphalts extracted from the above sections have been referred to in this report as simply Nos. 224 and 242 respectively.

The general properties of the surfacing, base course, subgrade and extracted asphalts, pertaining to the above highway sections are given in TABLES II to IV.

3.2 Analysis

TABLE II shows that the asphalts used were from two different refineries but of the same penetration grade. The age of the pavement sections 224 and 242 were four and three years respectively. The thicknesses of surfacing on both the pavement sections were practically the same. The

TABLE II

PHYSICAL PROPERTIES OF SURFACES*

	No. 224	No. 242
Cracks, average	348/mile	Nil
Thickness (ins) Surface	4.3	4.1
Base	6.7	8.7
Total	11.0	12.8
Age, years	4	3
Asphalt, refinery	1	5
Penetration - grade	150/200	150/200
Mixture Design		
75 Blow Marshall Stability	1310	1540
Flow (.01 in.)	9	10
Asphalt Content	5.9	5.8
Unit Weight	144.5	145.2
Voids %	3.4	3.6
V.M.A. %	14.5	15.0
V.F. (%)	76.6	76.0

* Data shown is taken from the Highways Division, Research Council of Alberta.

TABLE III

PROPERTIES OF BASE COURSE AND SUBGRADE*

Base Course	No. 224	No. 242
% Fines #200	9	9
γ_d	138.0	134.2
Wn (%)	3.2	4.3
S (%)	51.6	49.5
Subgrade**		
W_L (%)	43	47
I_p (%)	25	30
Class	CL	CL - CI
γ_d	113.8	101.4
W_n (%)	14.1	23.1
S (%)	79.3	94.4

** The subgrade properties have been determined from 3 inch diameter undisturbed Shelby Tube samples. The above classification of subgrade is the average of a number of samples tested.

* Data shown is taken from the Highways Division, Research Council of Alberta.

TABLE IV

CHARACTERISTICS OF RECOVERED SAMPLES*

Recovered Sample Properties		No. 224	No. 242
Unit Weight		138.5	141.7
Asphalt Content		5.3	5.9
Voids (%)		12.4	10.4
V.M.A. (%)		19.2	18.3
V.F. (%)		35.4	43.2
Recovered Asphalt Properties			
Penetration	77°F	89	89
	39.2°F	19	34
	Ratio**	21	38
Viscosity (poises)	140°F, 10^{-3} $sec.^{-1}$	1.7×10^3 poises	3.8×10^3 poises
	1 $sec.^{-1}$	1.0×10^3	2.1×10^3
	77°F, 10^{-3} $sec.^{-1}$	36.1×10^5	28.9×10^5
	1 $sec.^{-1}$	7.4×10^5	12.5×10^5
	39.2°F, 10^{-3} $sec.^{-1}$	10×10^8	4.7×10^8
	1 $sec.^{-1}$	0.8×10^8	1.4×10^8

** Penetration Ratio = $\frac{\text{Penetration at 39.2°F, 200 gms, 60 secs.}}{\text{Penetration at 77°F, 100 gms, 60 secs.}}$

* Data shown have been taken from the Highways Division, Research Council of Alberta.

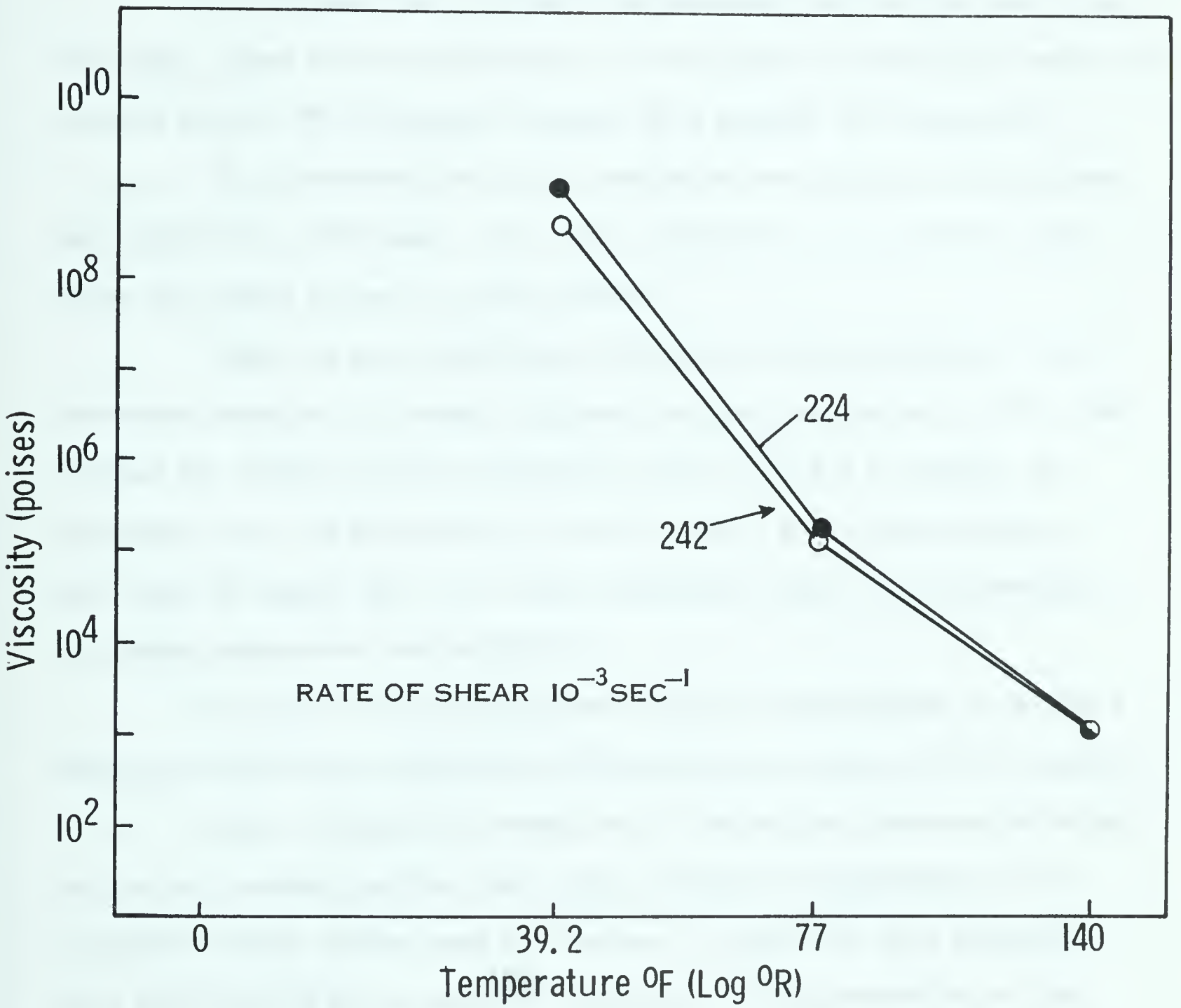


FIGURE I. TEMPERATURE-VISCOSITY RELATIONSHIPS

base course in section 224 was two inches less thick than that of 242. The test properties of the design mix for both the pavement sections were practically identical. Base course properties of the two sections were also very similar.

The subgrade soil for both the pavements were of the same classification. There was some difference in the degree of saturation, which for section 224 was 79.3 percent as against 94.4 percent for section 242.

The characteristics of the recovered core samples did not show any appreciable difference. The V.M.A. and percent air voids were well above the design values for both sections.

There was one significant difference in the properties of the recovered asphalts. Although they have the same penetration at 77°F, the cracked one showed a lower penetration value at 39.2°F as against the uncracked one. The penetration ratio of asphalt 224 is approximately half that of asphalt 242. The lower penetration ratio is an indication of higher temperature susceptibility.

The plot of the temperature-viscosity relationships in FIGURE 1 does not indicate any significant differentiation between the two asphalts.

Thus, although the properties of the various component materials of the two pavement sections were very similar, the properties of the recovered asphalt binder were not the same. Therefore, this investigation was directed to the study of the asphalt binder properties of the above sections.

CHAPTER IV

OUTLINE OF TESTING PROCEDURE AND PROGRAM

4.1 General

The testing program involved determination of the stress-strain characteristics of a large number of samples in tension at various film thicknesses, rate of extension and temperature. The magnitude of load was expected to be fairly high in the order of hundreds of pounds which could be easily measured, but the deformation very small, in the order of 10^{-4} inches. Therefore, a suitable and convenient method for plotting load versus deformation of the films was evolved with the use of electrical apparatus. The method of film formation, load measurement, deformation measurement, plotting of load-deformation curves and temperature regulation are discussed in the following paragraphs.

The Wykeham Farrance Model 57 testing machine with special attachments was used to apply load at various rates of deformation. Test blocks were made of stainless steel, AISI Alloy number 431, since it could be machined and polished to a minimum of surface irregularities.

4.2 Film Formation

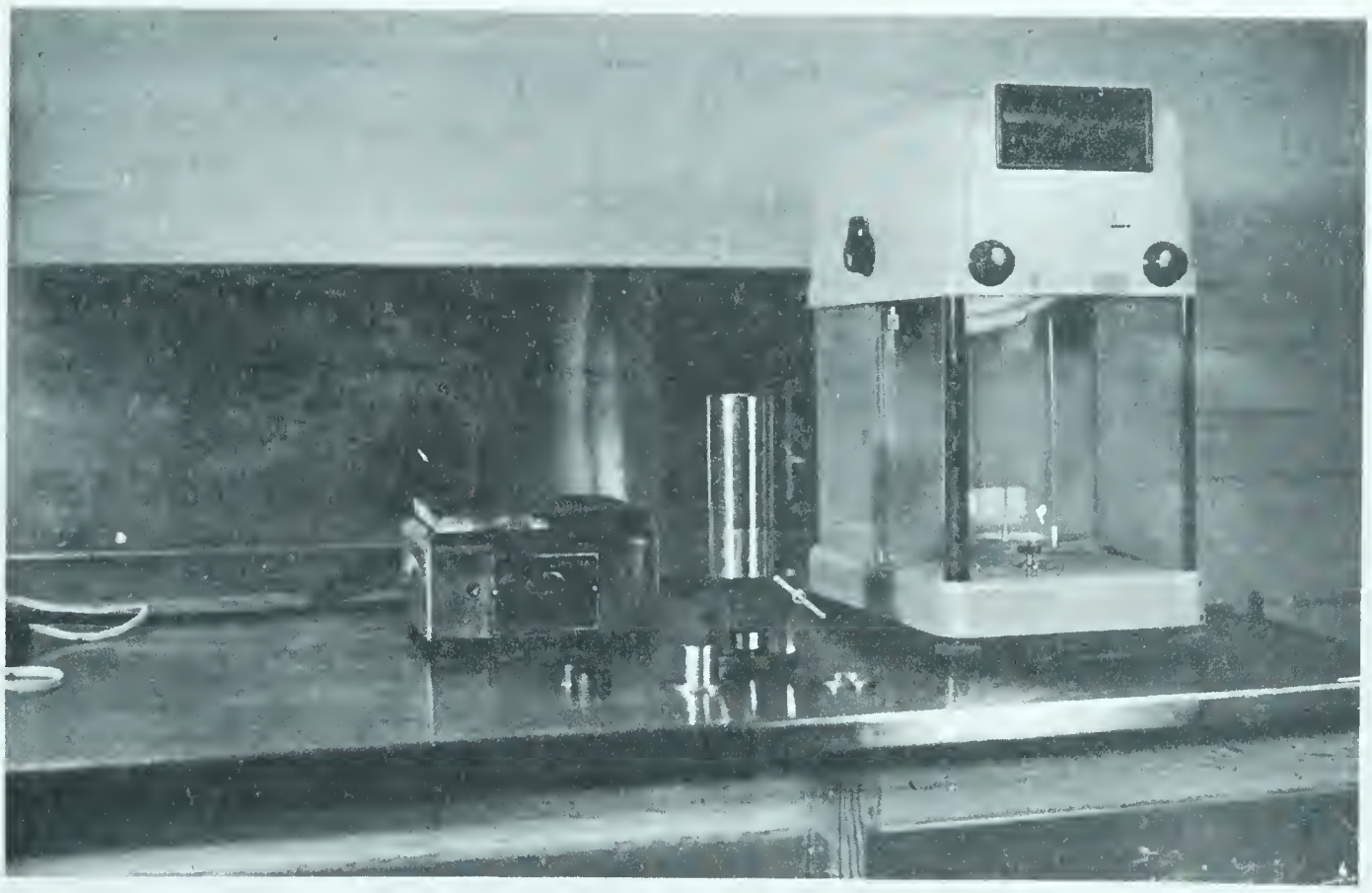
Asphalt specimens were prepared by sandwiching small amounts of asphalt between two stainless steel hardened blocks, one inch in diameter and half an inch thick. The test blocks were cleaned with trichlorethylene and accurately weighed to the nearest one thousandth of a gram on an electronic analytical balance. The test blocks and asphalts were heated

gently to facilitate film formation without further hardening. Approximate amounts of asphalt were placed on the test blocks and spread over the surface by squeezing and rotating the test blocks. The test blocks with the sandwiched asphalt film were then placed in a film forming device, Hallikainen Instruments Model 1147, which kept the faces parallel with the weight of its plunger while the asphalt cooled to room temperature. The details of the test blocks and the film forming device are given in Plate 1A and Appendix B.

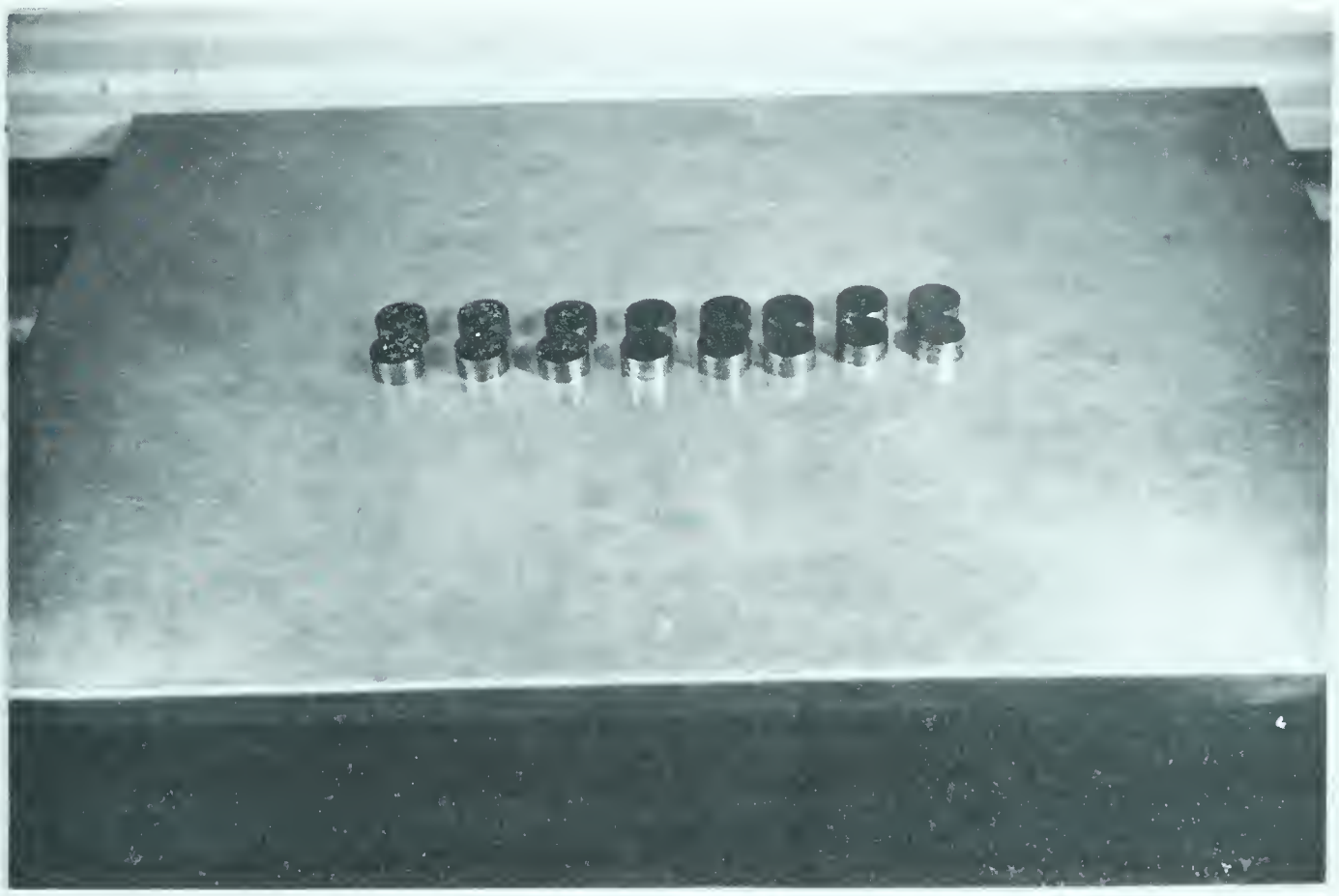
After the films were formed the excess asphalt on the edges of the test blocks were cleaned carefully with the solvent and weighed. The thickness of the film was calculated in microns from the weight, specific gravity of the asphalt and the area of the test blocks. All samples were maintained at the test temperature from half to two hours before testing.

4.3 Load Measurement

A thin walled aluminium cell, Plate 2A, one inch active length and .075 inch wall thickness was designed and fabricated for the measurement of the anticipated load up to 2000 lbs. A 120-ohms electrical bridge circuit was mounted on the cell with 3 volts power supply. The bridge was connected to an Acromag Amplifier to read suitably the loads of different magnitude. The amplifier was then connected to an X-Y recorder to read loads on the Y-axis. The recorder was pre-calibrated for different ranges of loads, the details of which are given in Appendix B. The maximum sensitivity obtained was 1" = 20 lbs on the recorder. The load cell was connected to the test blocks and the testing machine by specially designed attachments which provided flexibility and alignment of the test blocks. The gear driven machine could be operated over a range of .075 to .000045 in/min.

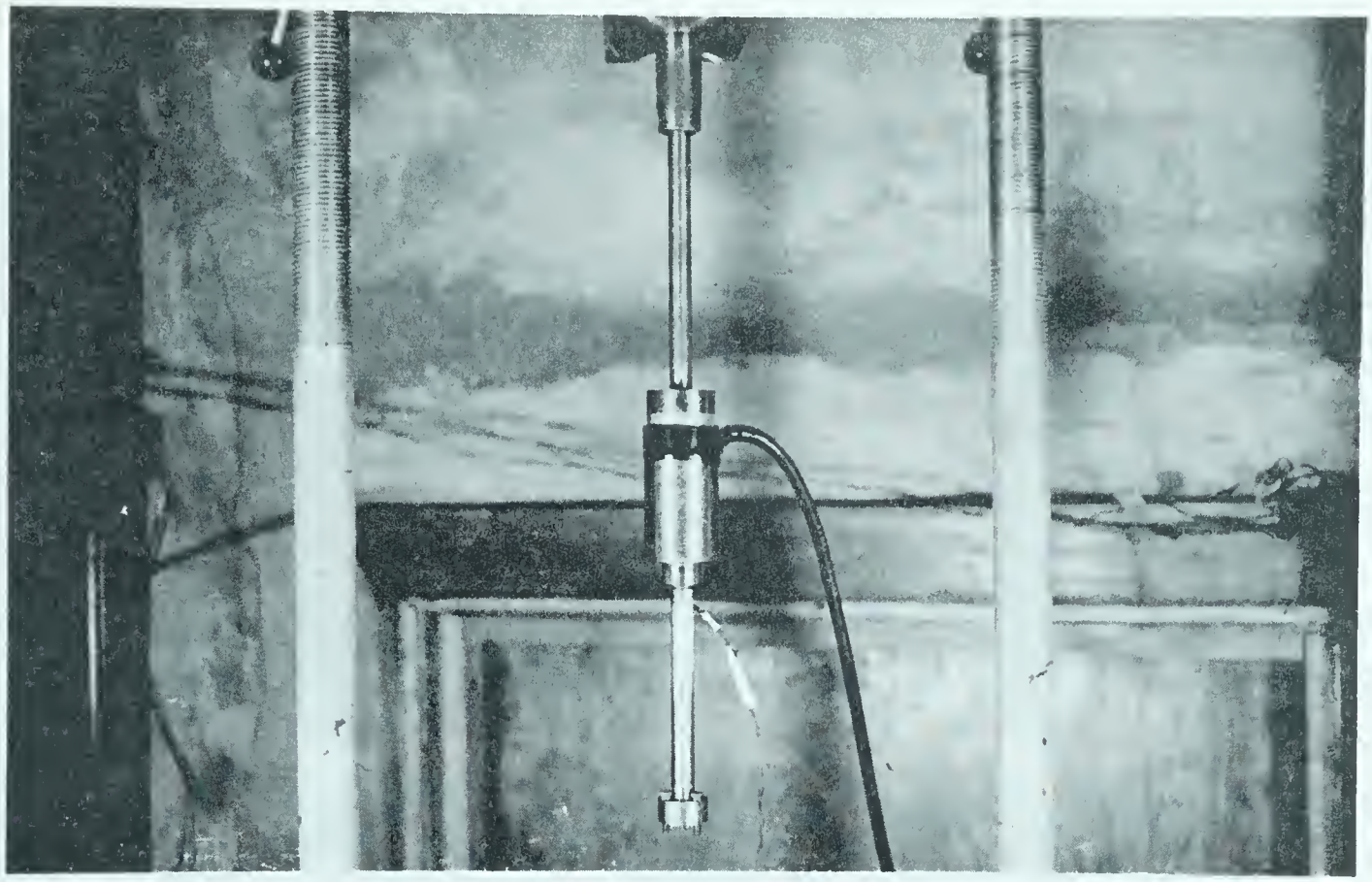


[A] FILM FORMATION EQUIPMENT

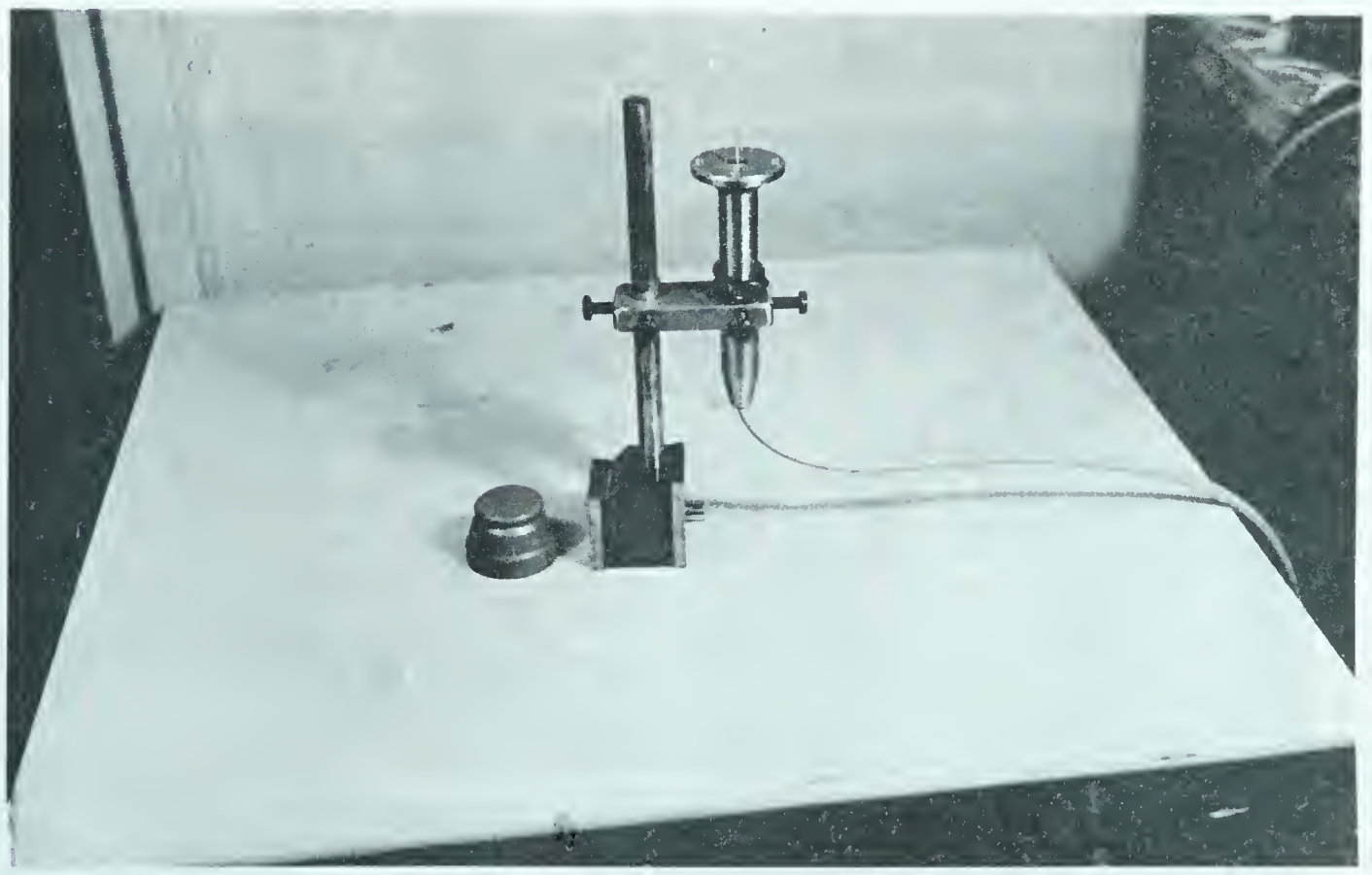


[B] ASPHALT SAMPLES AFTER TEST

PLATE I

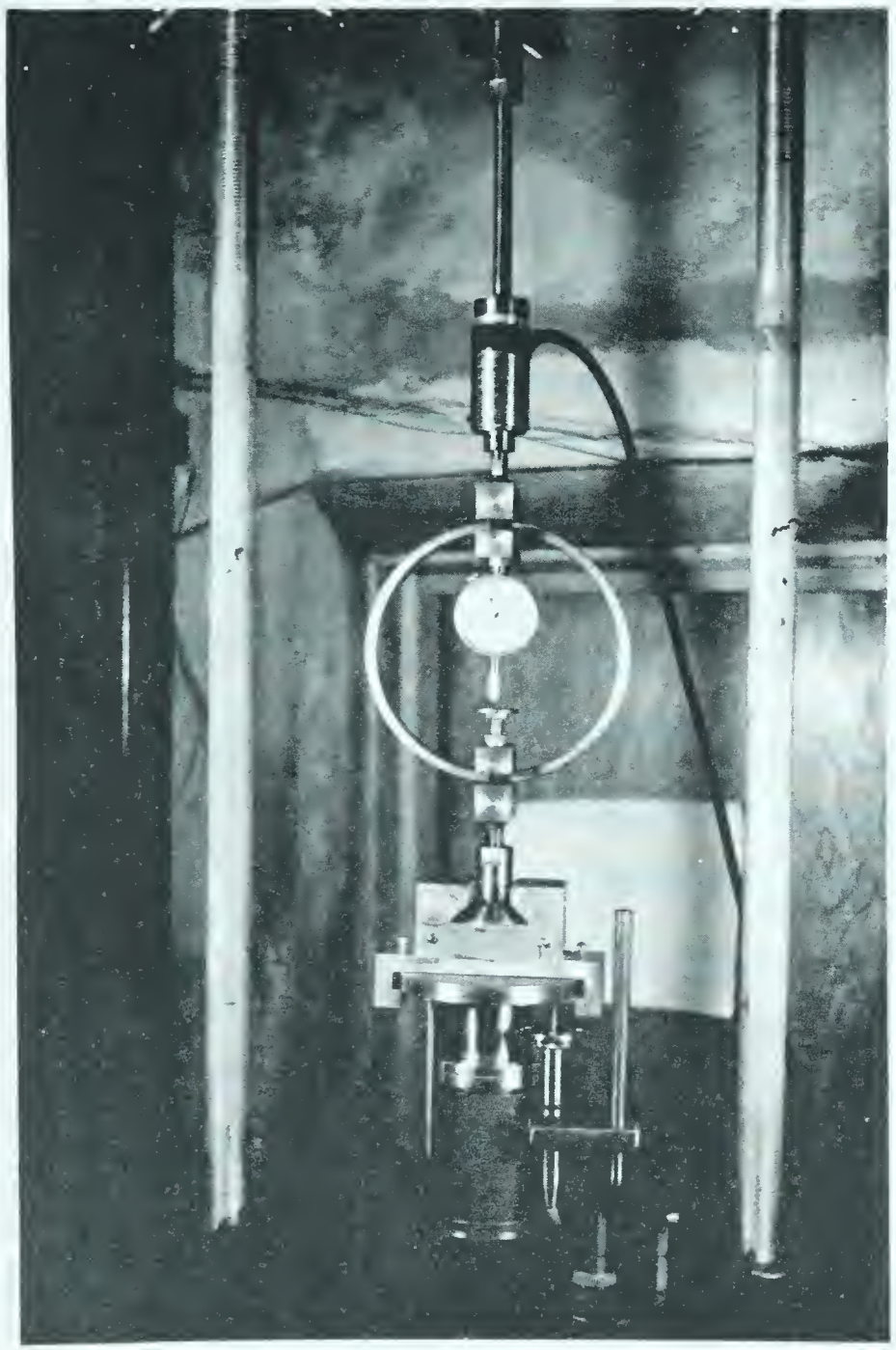


[A] LOAD CELL

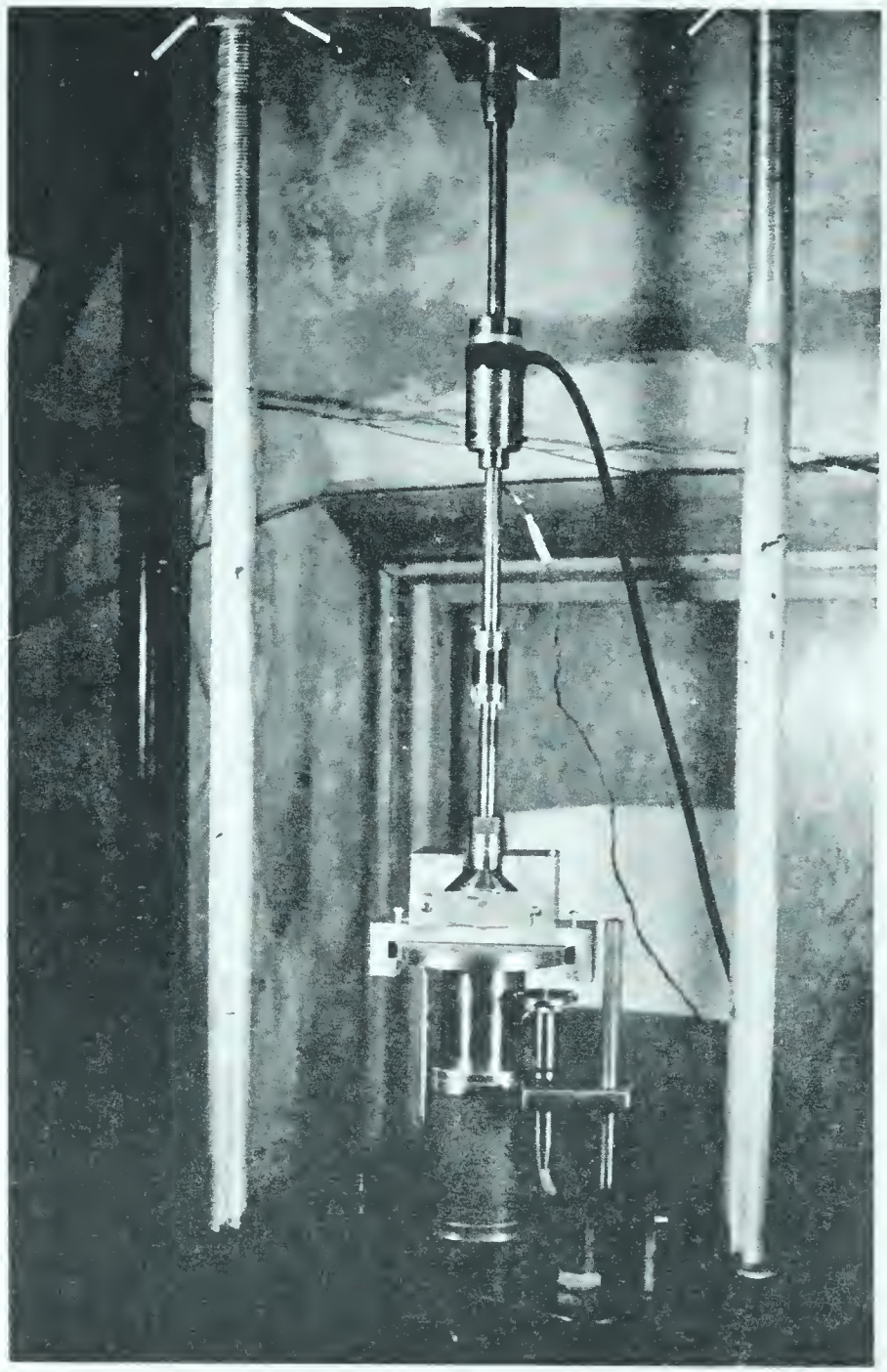


[B] DEFORMATION TRANSDUCER

PLATE 2



[A] CALIBRATION OF LOAD CELL



[B] TENSION TESTING OF ASPHALT FILMS

PLATE 3

4.4 Strain Measurement

The measurement of strain was done with a Sanborn Deformation type Transducer Model 580 and is shown in Plate 2B. It was mounted on a magnetic stand and placed in contact with the lower moving head of the machine. The transducer was connected to a Sanborn Preamplifier and an X-Y recorder. The strain was recorded on the X-axis. The transducer worked on A.C. power supply and the recorder on D.C. power supply, therefore an A.C./D.C. transformer was used in the circuit. The deflections on the recorder due to vertical movements of the transducer probe was calibrated with a sensitive dial gauge. The details of calibration are given in Appendix B.

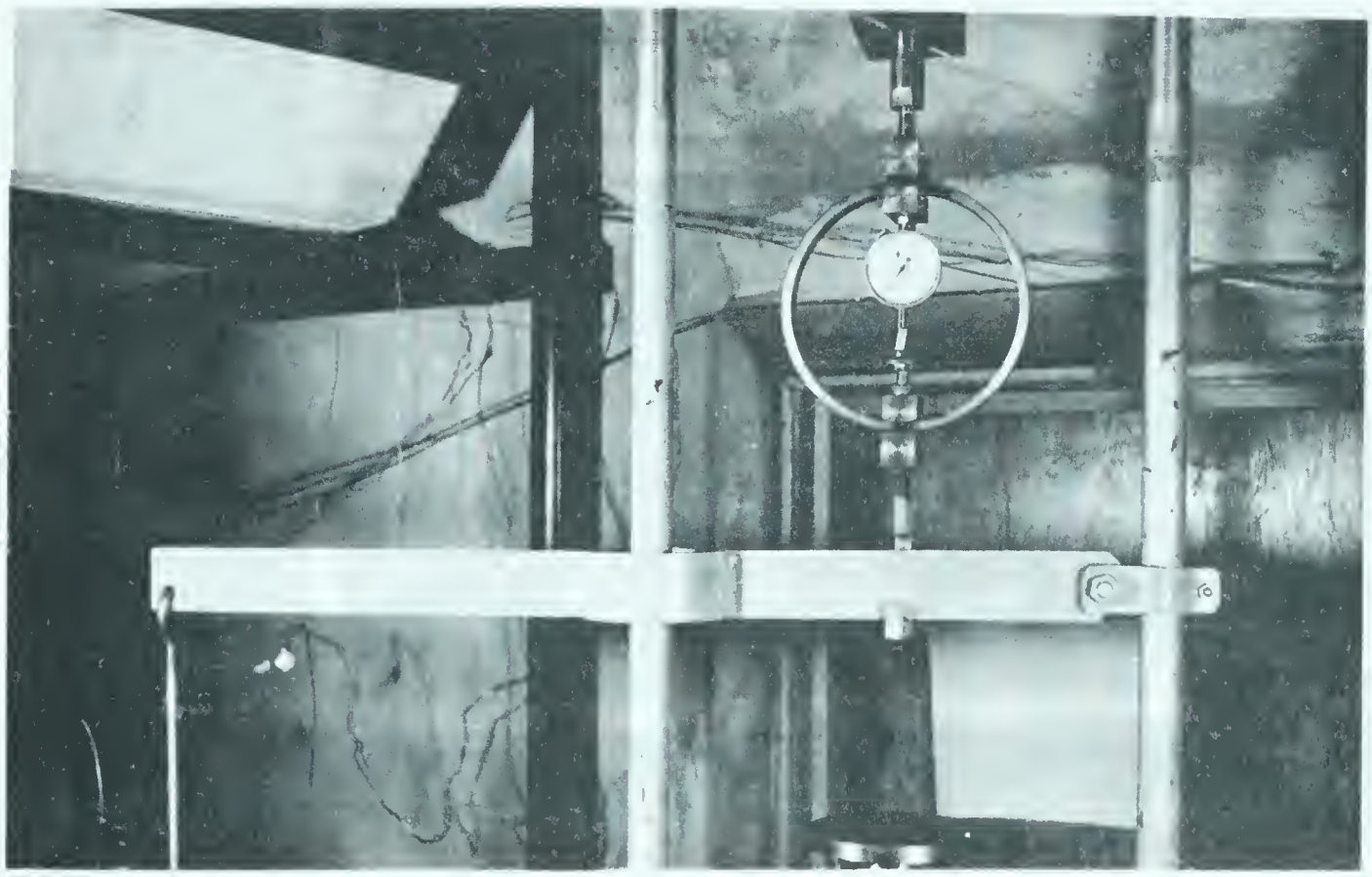
4.5 Recording of Load and Deformation

The entire recording unit (Plate 4A) was placed in a room adjacent to a temperature controlled room in which the machine was placed. With the load signal being on the Y-axis and deformation on the X-axis, a load-deformation curve was plotted as the test was in progress. This provided a very convenient method of observation especially in view of the large number of tests, short duration of each test and colder temperatures of testing.

4.6 Temperature Regulation

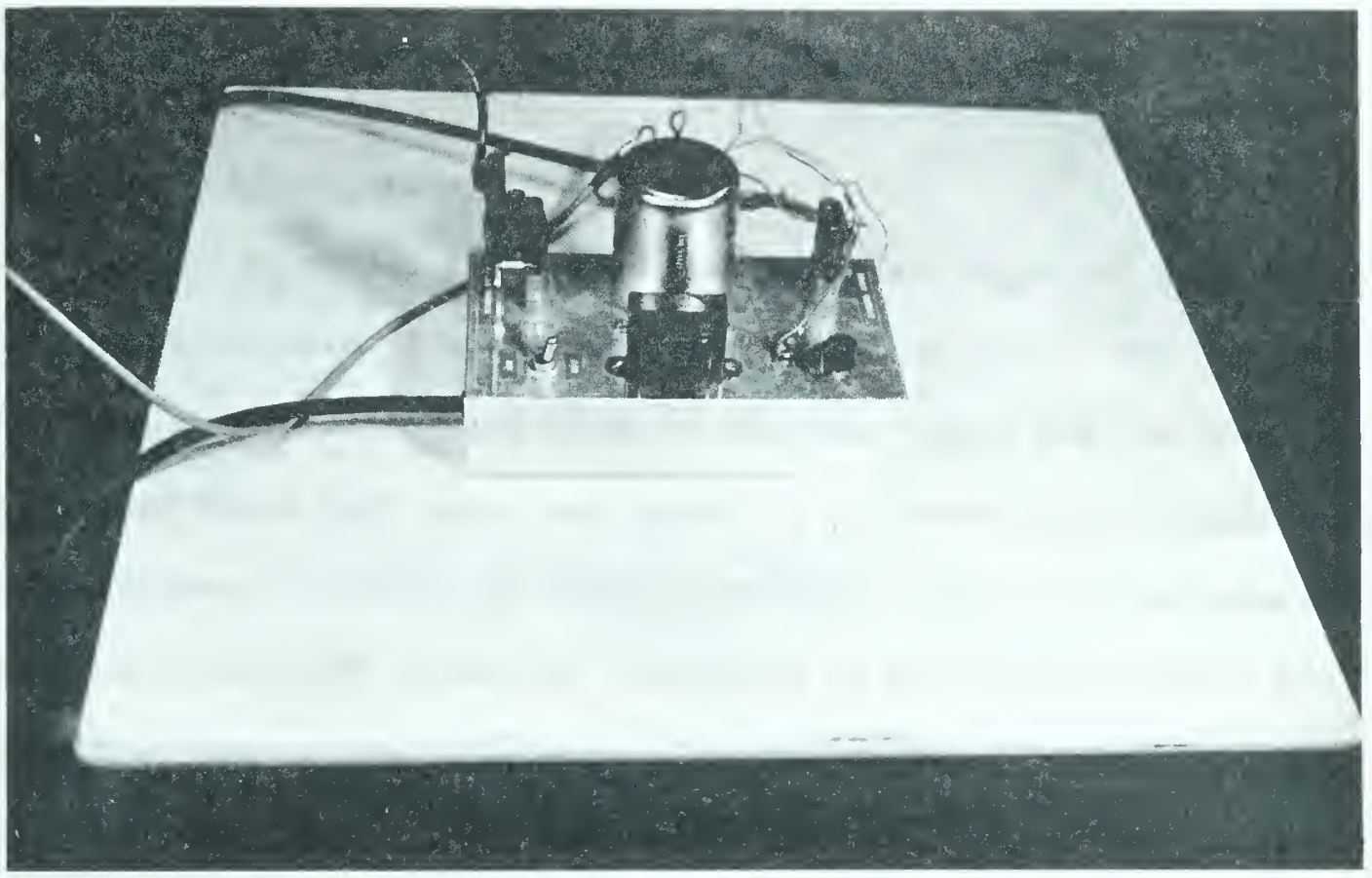
The entire testing machine and other accessories were placed in a temperature controlled room, the recorder and amplifiers being placed in an adjacent room as shown in Plate 4A. The room was fitted with heavy insulated doors and a refrigerating unit capable of bringing down the temperature to about -40°F. The samples of asphalt for the test were

[A] RECORDING EQUIPMENT

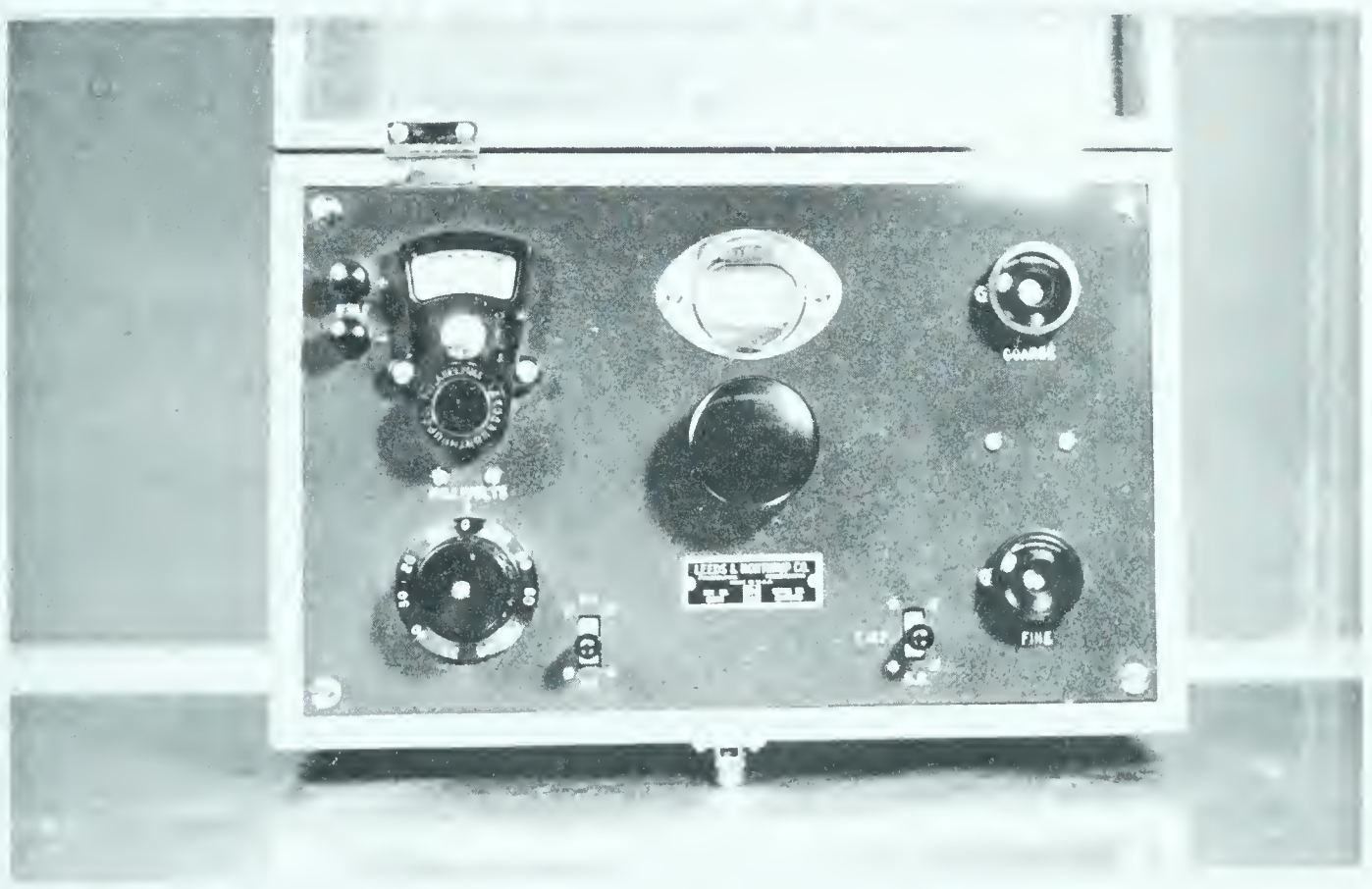


[B] CALIBRATION OF PROVING RING

PLATE 4



[A] ACROMAG AMPLIFIER



[B] PORTABLE POTENTIOMETER

PLATE 5

stored in this room for at least half an hour before testing.

4.7 Temperature Measurements

A pair of copper-constantan thermocouples in series were used to record the temperature of the sample at the time of test. One junction of the thermocouple was placed close to the test block and the other in an ice cooled water bath which was stored in a thermos flask placed outside the chamber. A Leeds and Northrup portable type of potentiometer was used to measure the potential difference in millivolts between the two junctions due to the difference of temperatures. The potentiometer was pre-calibrated for various temperature differences of the two junctions by keeping one of the junctions in ice cold water and the other in a water bath at the desired temperature. The calibration checked very well with the calibration chart supplied with the instrument. This chart was then used to determine the temperature of the sample at the time of the test as well as the temperature of air.

4.8 Testing Program

Both the asphalts selected were tested in tension at various temperatures, rate of extension and film thicknesses. The variables selected were studied one at a time, while holding the others constant. The range of variables studied is presented in TABLE V.

TABLE V - TESTING PROGRAM

Asphalt	Nos. 224 and 242 of Highway No. 57A
Film Thickness	10 to 1000 microns
Rate of Extension	.1, .02, .004 and .0008 inch/min.
Temperature	77°, 50°, 40°, 30°, 20°F.

A set of load deformation curves of each of the asphalts were determined for various film thicknesses, keeping the temperature of the room and rate of extension of the machine constant. Six to ten samples were tested in order to get a suitable film thickness-tensile strength curve for each set.

The machine was then adjusted to another rate of extension, maintaining the same room temperature, and another set of load-deformation curves was determined for various film thicknesses. A series of similar tests were performed for the various rates of extension.

The temperature of the room was then adjusted to next value and the above mentioned sets of observations taken.

Since the object of the investigation was to determine the film-strength of the asphalt samples, all such cases of failure in adhesion between asphalt and metal surface, were discarded.

CHAPTER V

PRESENTATION OF TEST RESULTS

5.1 Description of Plotted and Tabular Results

This chapter presents the major results, taken from the numerous observations of the complete testing program. The results have been arranged to show the fundamental tensile properties of the two asphalts tested as well as their differences in behaviour. A slow rate of extension of .004 inch per minute has been selected for showing tensile strength - film thickness relationships. A film thickness of 300 microns has been selected arbitrarily to show the difference in behaviour of the two asphalts in tensile strength, unit strain and stiffness modulus at various temperatures and .004 inch per minute rate of extension. A brief description of each figure and table, included in this chapter, follows.

FIGURE 2 shows the results of the tension tests on a very thin and a very thick asphalt film. The curve A for the thin film shows what may be described as brittle failure while curve B for the thick film exhibits plastic failure. Similar curves were obtained for both the asphalts tested in thin and thick films. These curves have been taken from various load-deformation curves plotted by the recorder.

FIGURES 3 and 4 show the tensile strength-film thickness relationships for both the asphalts for the rate of extension of .004 in /min

FIGURES 5 and 6 show the relationship between film thickness and total deformation to failure at 77°F and 50°F respectively for the rate of

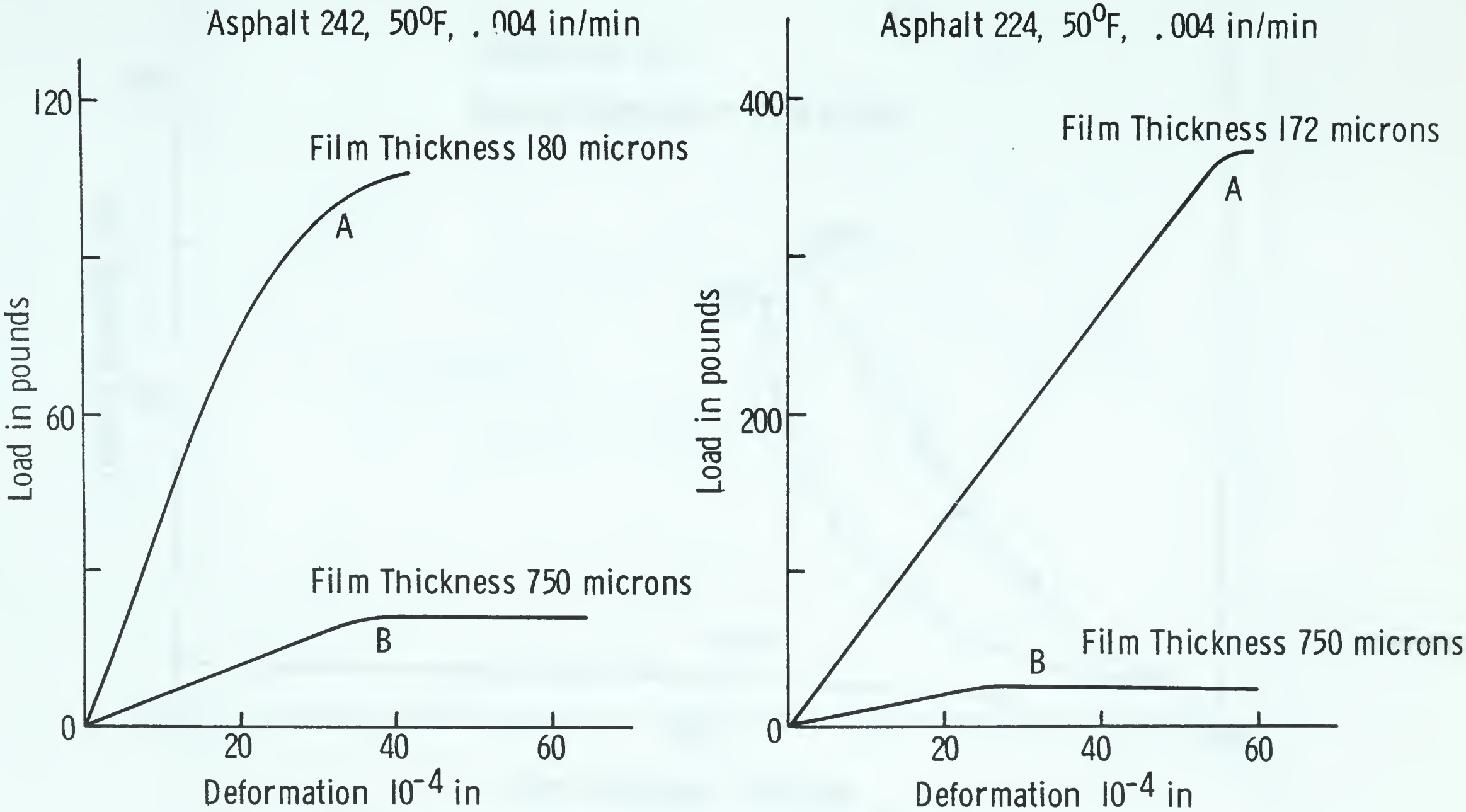


FIGURE 2. LOAD DEFORMATION CHARACTERISTICS

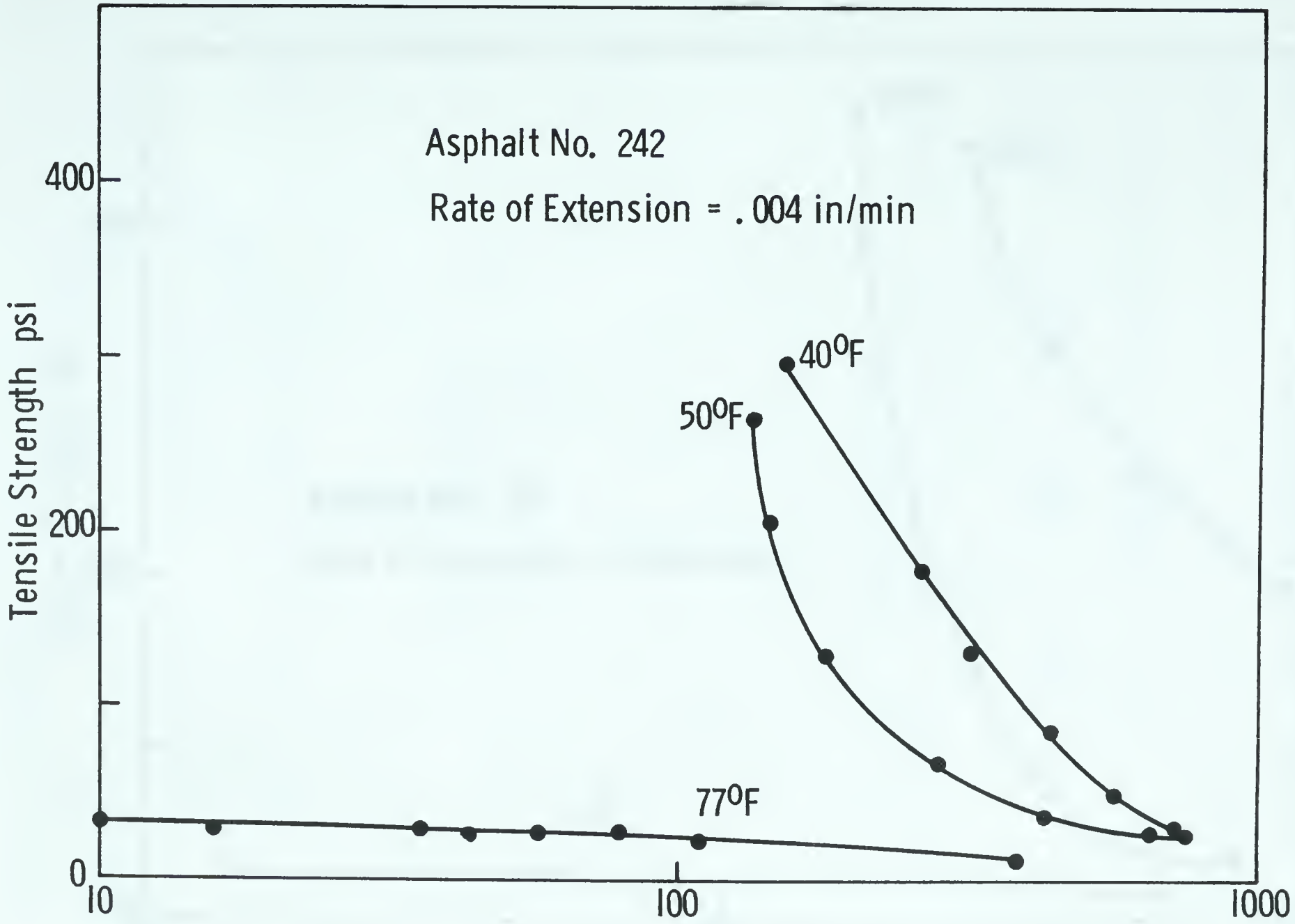


FIGURE 3. FILM THICKNESS - TENSILE STRENGTH RELATIONSHIPS

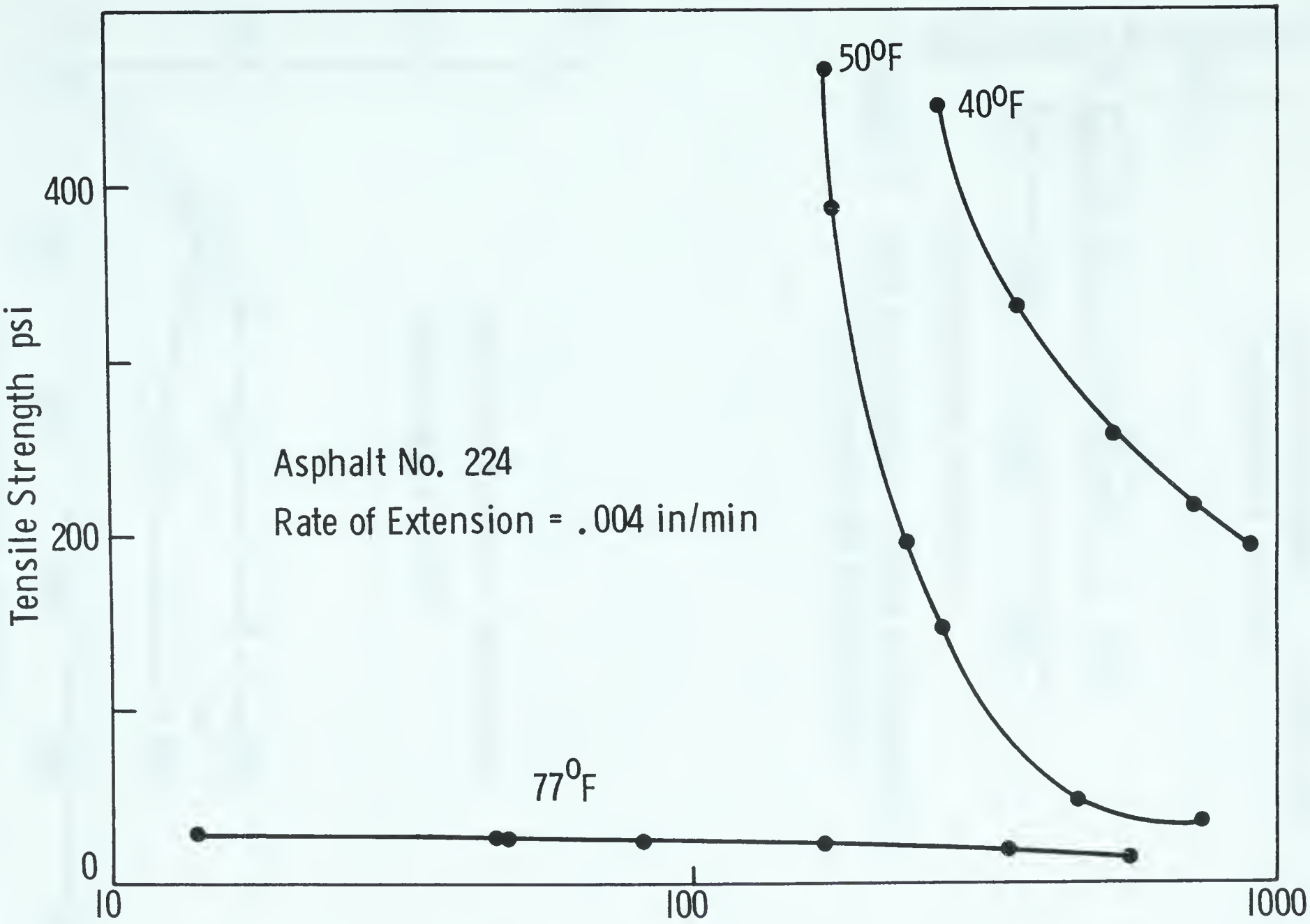


FIGURE 4. FILM THICKNESS - TENSILE STRENGTH RELATIONSHIPS

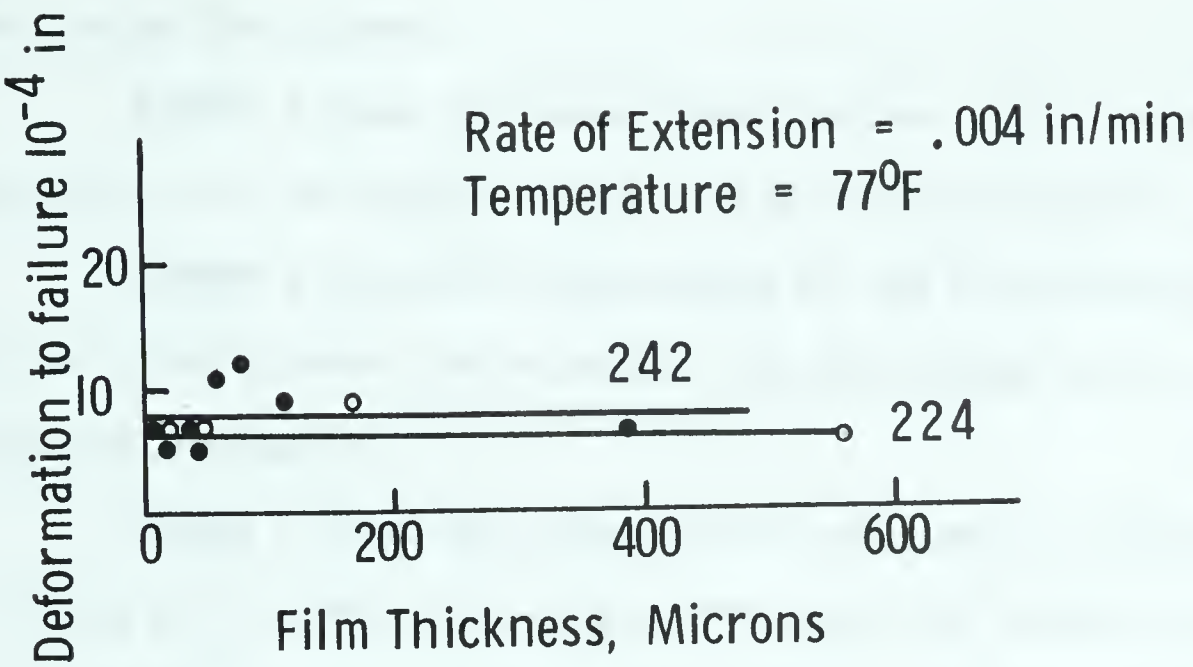


FIGURE 5. FILM THICKNESS - TOTAL DEFORMATION TO FAILURE RELATIONSHIPS

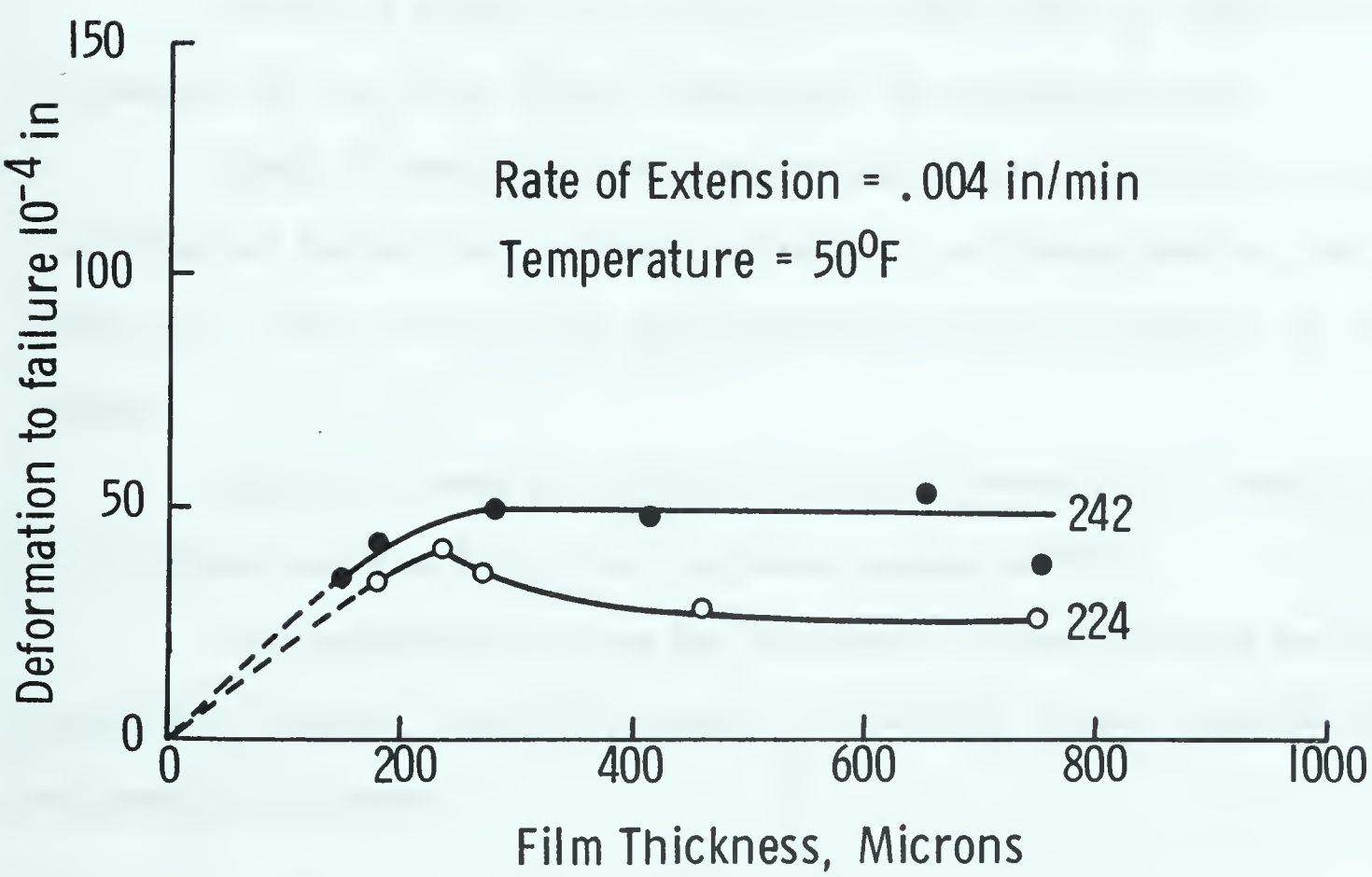


FIGURE 6. FILM THICKNESS - TOTAL DEFORMATION TO FAILURE RELATIONSHIPS

extension of .004 in/min.

FIGURE 7 shows the relationship of the rate of extension and film strength for the 300 microns thick film at 50°F for both the asphalts.

FIGURE 8 shows the relationship of the film strength and temperature for a 300 microns film thickness and .004 in/min rate of extension for both the asphalts.

FIGURE 9 shows the effect of the temperature on the unit strain to failure for the 300 microns thick film and .004 in/min rate of extension for both the samples.

FIGURE 10 shows the variation of stiffness modulus with temperature for the 300 microns thick film and .004 in/min rate of extension.

FIGURE 11 shows the effect of rate of extension on stiffness modulus of 300 micron thick film and test temperature of 50°F.

FIGURE 12 shows the difference of unit strain to failure for the two samples on log scale versus temperature on arithmetic scale.

TABLE VI shows the data computed from the various curves and shows the effect of temperature on tensile strength, stiffness modulus, unit strain for a film thickness of 300 microns and rate of extension of .004 in/min.

TABLE VII shows the effect of rate of extension on tensile strength and stiffness modulus for 300 micron thick sample at 50°F.

The Appendices contain two theories of film thickness and tensile strength of asphalt, detailed procedure of testing, sample calculations, and sample data sheets.

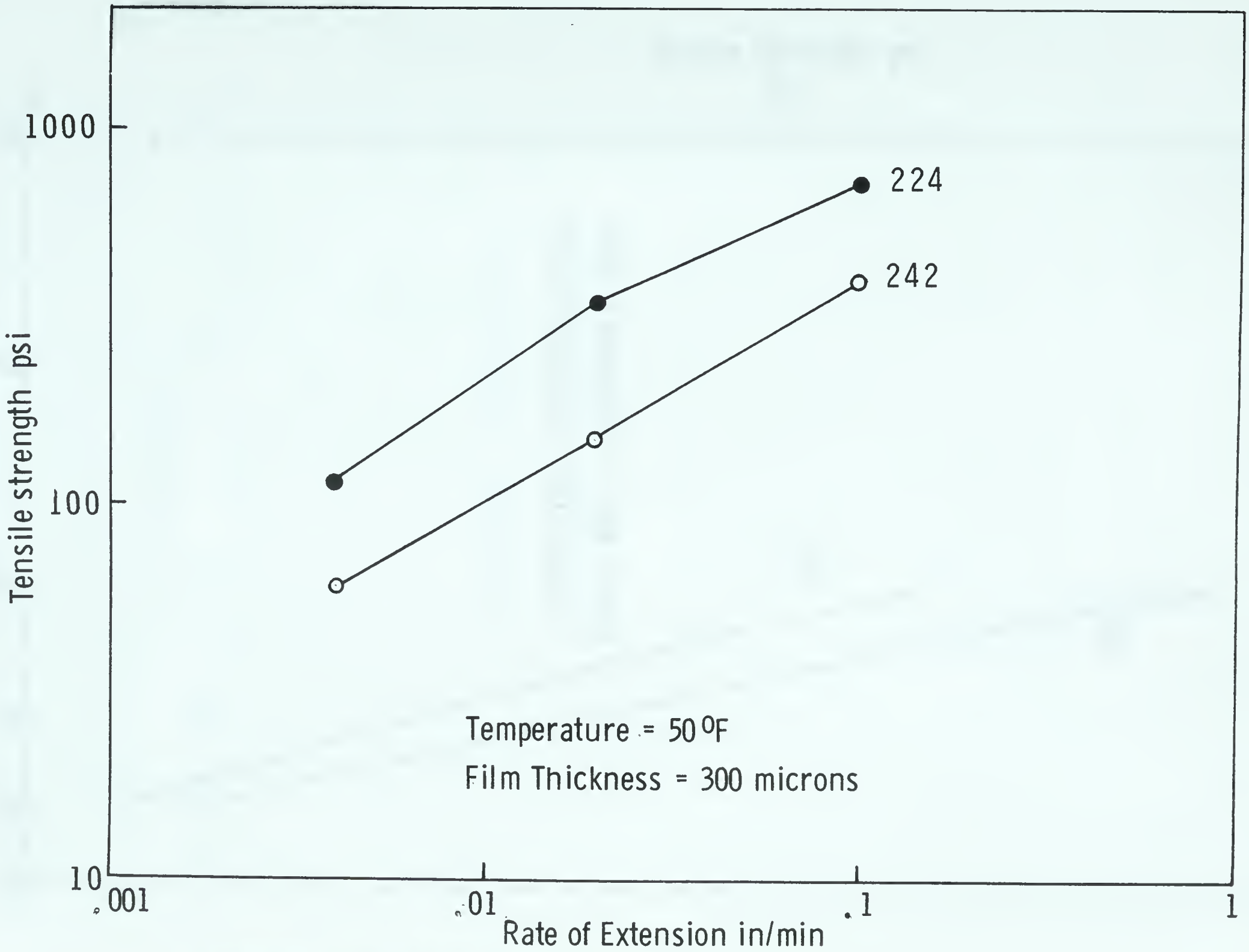


FIGURE 7. TENSILE STRENGTH - RATE OF EXTENSION RELATIONSHIPS

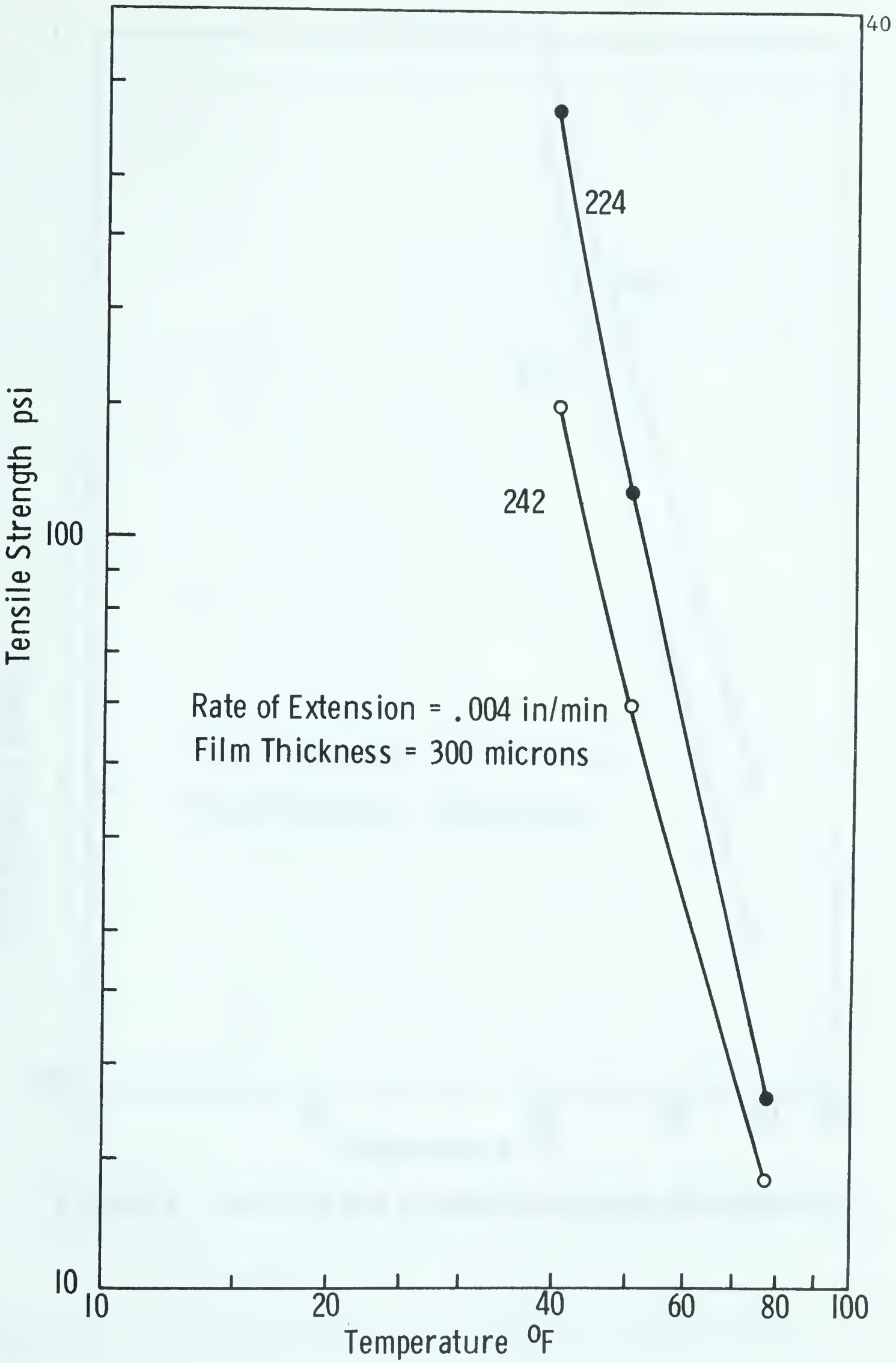


FIGURE 8. TENSILE STRENGTH - TEMPERATURE RELATIONSHIPS

I.

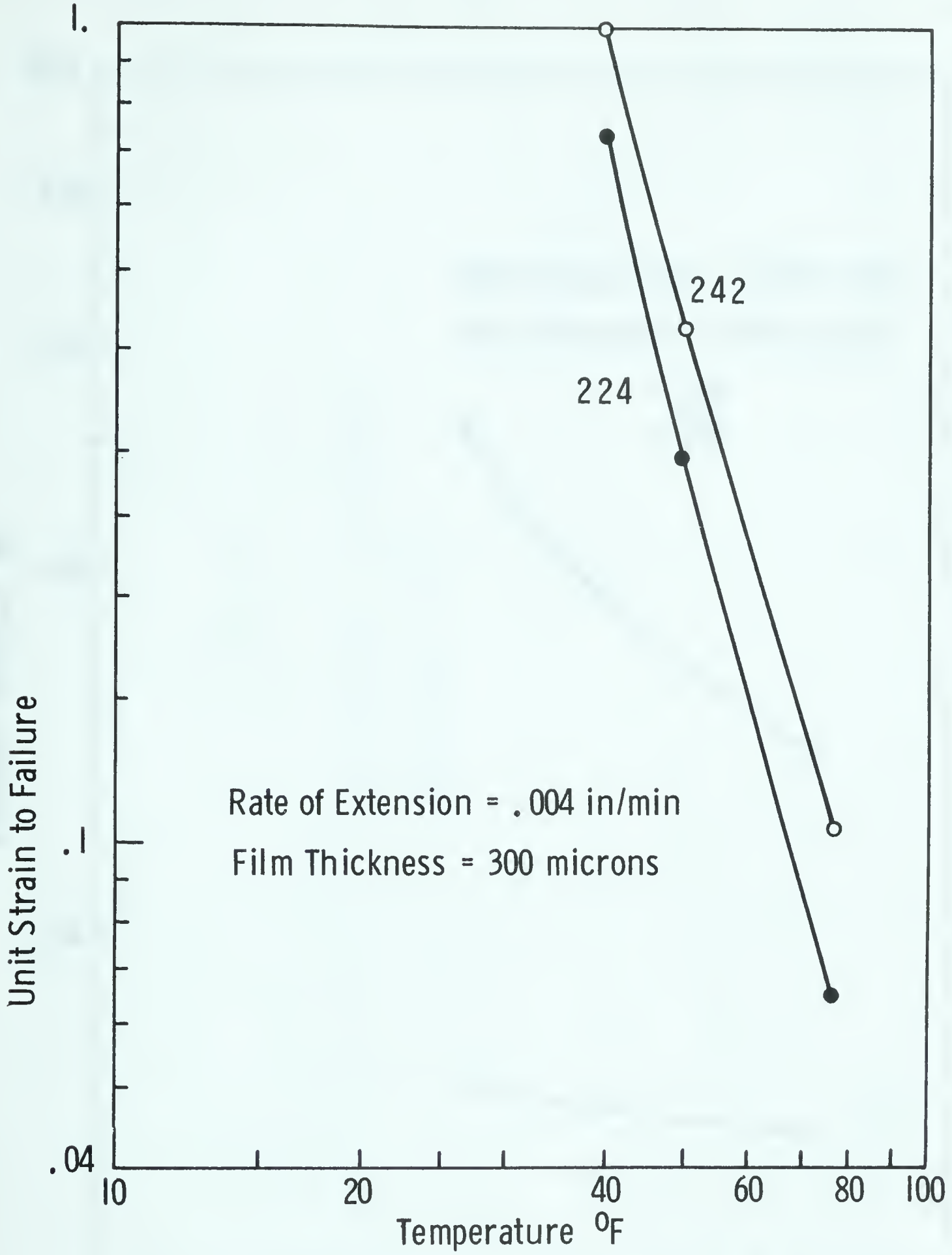


FIGURE 9. UNIT STRAIN - TEMPERATURE RELATIONSHIPS

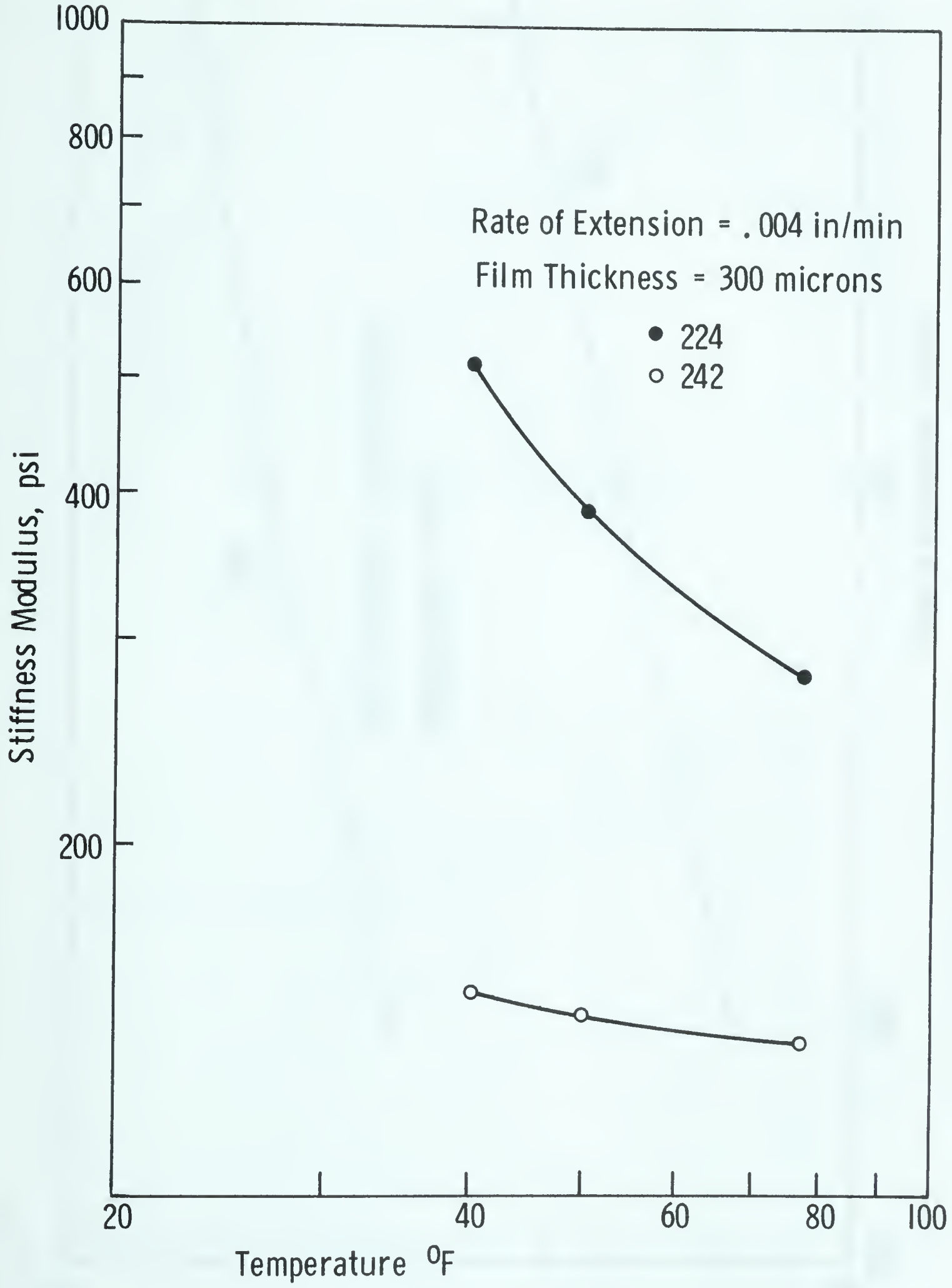


FIGURE 10. STIFFNESS MODULUS - TEMPERATURE RELATIONSHIPS

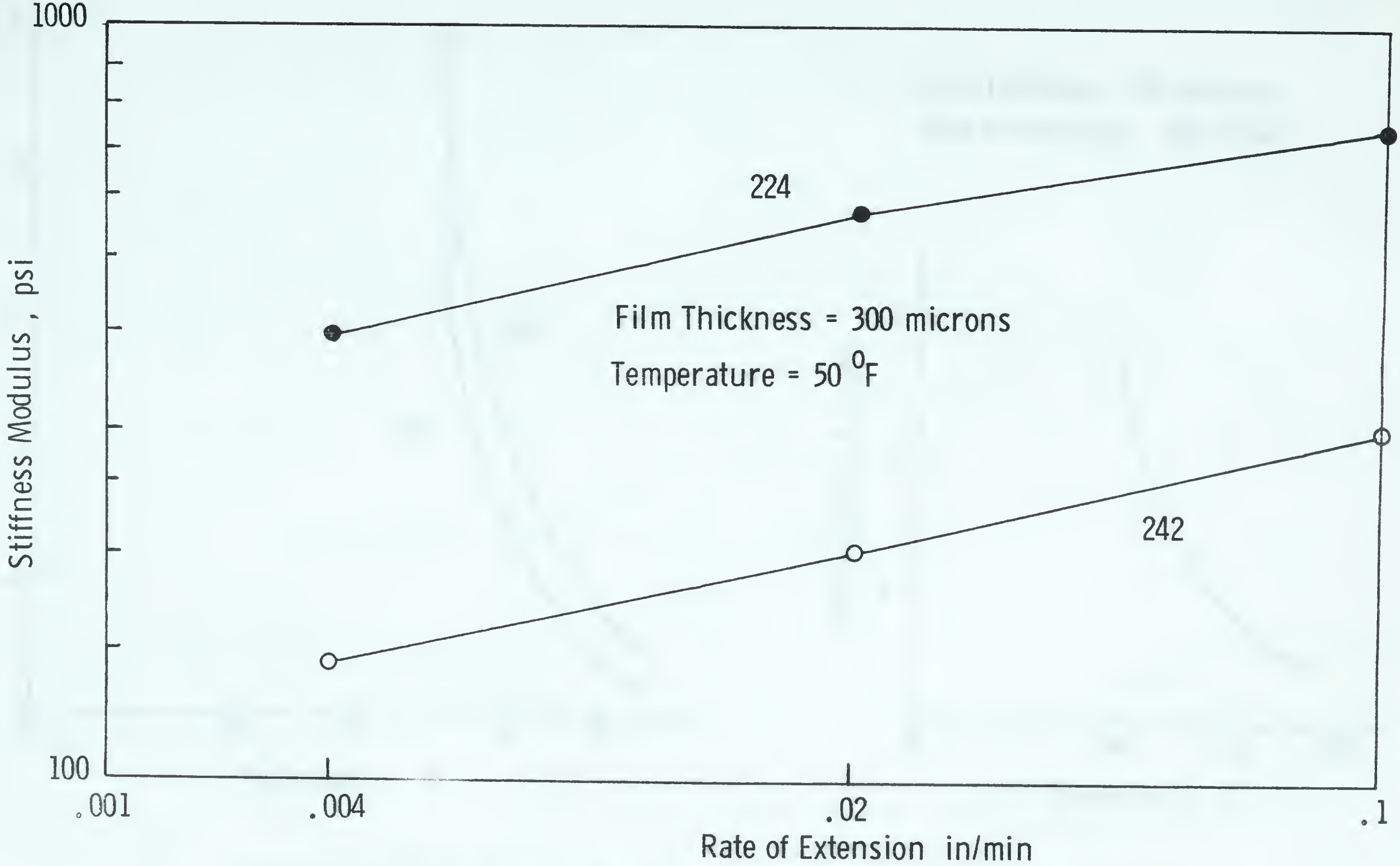
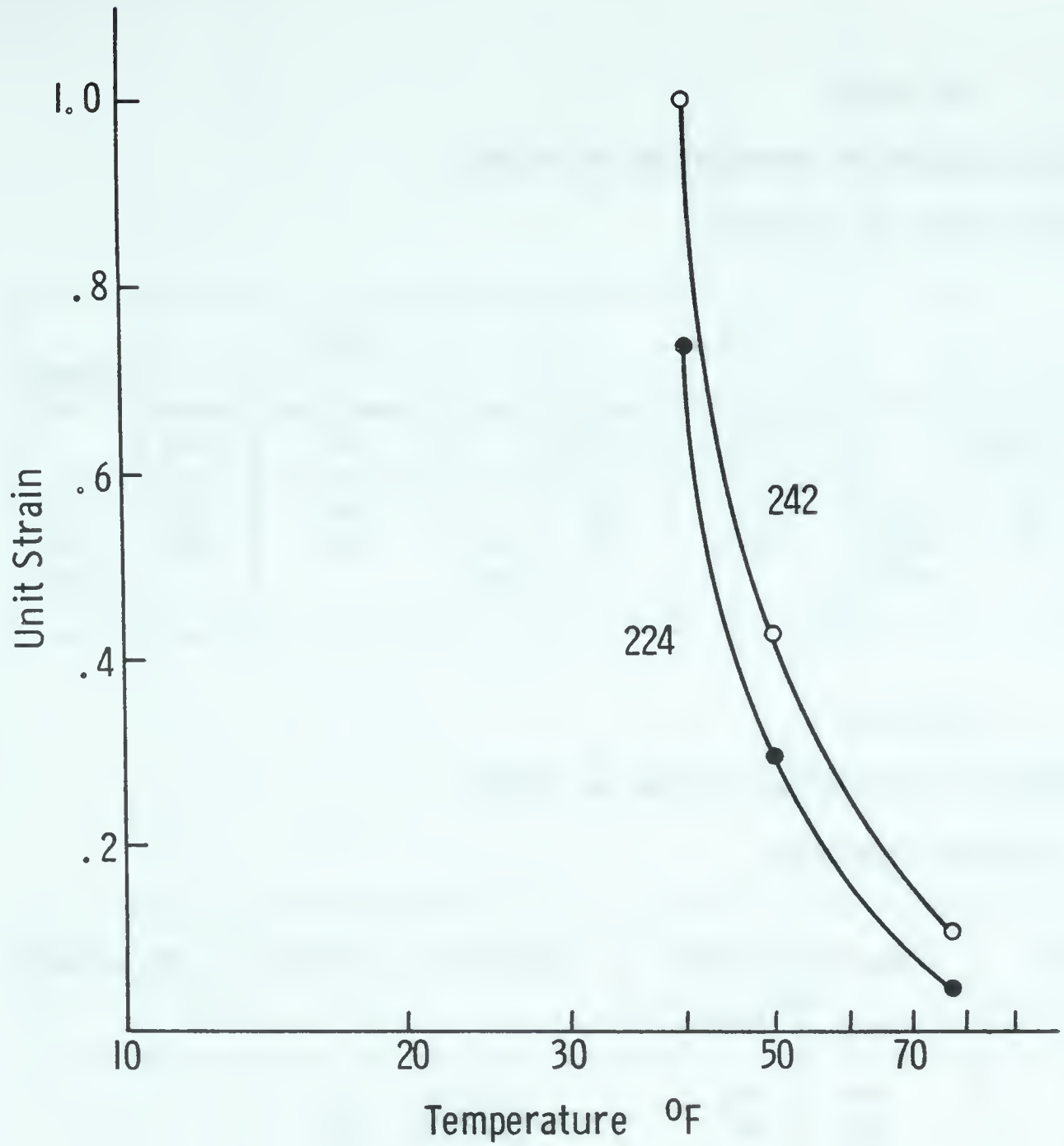


FIGURE II. STIFFNESS MODULUS - RATE OF STRAIN RELATIONSHIPS



Film Thickness: 300 microns
Rate of Extension: .004 in/min

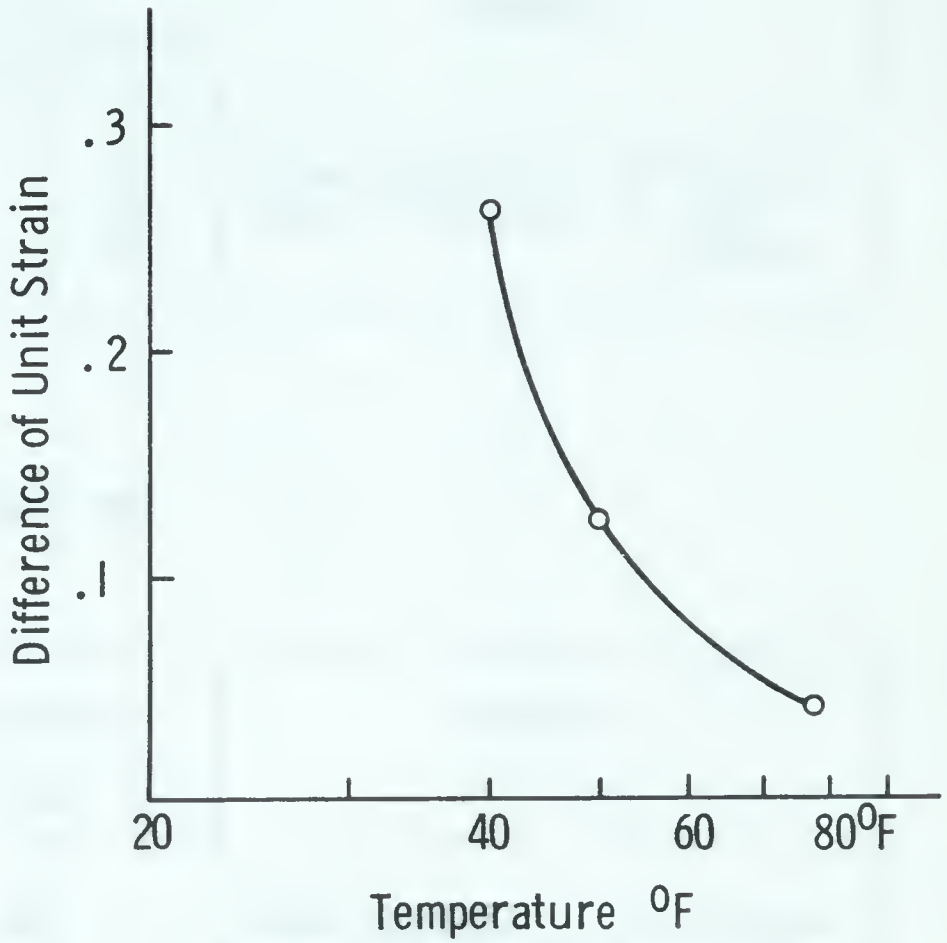


FIGURE 12. UNIT STRAIN TO FAILURE - TEMPERATURE RELATIONSHIPS

TABLE VI

EFFECT OF TEMPERATURE ON TENSILE STRENGTH, STIFFNESS MODULUS AND UNIT STRAIN

Sample no.	40°F			50°F			77°F			Remarks
	Stress psi	Stiffness psi	Strain	Stress psi	Stiffness psi	Strain	Stress psi	Stiffness psi	Strain	
242	150	150	1.0	60	142	.422	14	135	.104	Film Thickness = 300 microns
224	380	515	.738	115	385	.298	18	280	.064	Rate of Extension = .004 in/min.
Diff.			.262			.124			.040	

TABLE VII

EFFECT OF RATE OF EXTENSION ON TENSILE STRENGTH AND STIFFNESS MODULUS

Serial No.	Rate of Extension	Tensile Strength psi		Stiffness Modulus psi		Remarks
		242	224	242	224	
1	.1 in/min.	385	700	300	740	
2	.02 in/min.	150	320	200	560	Film Thickness = 300 microns
3	.004 in/min.	60	115	142	385	Temperature = 50°F

CHAPTER VI

DISCUSSION AND INTERPRETATION OF RESULTS

6.1 General

This chapter contains detailed interpretation and discussion of the test results. Since this investigation was concerned with comparing the tensile properties of two asphalts which have behaved quite differently in the field, the test results have been presented in such a manner as to readily show any differences. The test results have also been examined in the light of various strength theories propounded by some authors. The interpretation of these results applied to the problem of pavement cracking, is included at the end of this chapter.

6.2 Load-Deformation Characteristics

The Load-Deformation characteristics of viscoelastic materials is dependent upon the rate of loading and temperature. Recent studies have shown that these characteristics are also a function of film thickness. The present investigation also confirms this fact.

Typical load-deformation curves for thin and thick films of both asphalts tested under identical conditions of temperature and rate of extension are shown in FIGURE 2. The failure in thin films was characterized by instantaneous separation, cavitation and small honeycomb patterns on the surface of the asphalt and has been referred to as a brittle failure.

The failure in thick films showed plastic deformation, flow and

necking in the asphalt film, cavitation and formation of filaments and larger honeycomb patterns on the failure surface. This type of failure has been referred to as a viscous failure. It was observed that the number of honeycomb patterns increased as the film thickness decreased. The lowering of temperature had a similar effect.

6.3 Film Thickness-Tensile Strength Relationship

The relationships of film thickness versus tensile strength are plotted in FIGURES 3 and 4 on a semi-log plot for asphalts 242 and 224 respectively for a rate of extension of .004 inch per minute. The shape of the curves indicate that the tensile strength increases as the film thickness decreases. It is noticed that there is initially a large decrease in tensile strength with increasing film thickness, at temperatures of 40°F and 50°F. At 77°F there is only a very small decrease in tensile strength.

6.4 Amount of Deformation to Failure

The theoretical and experimental investigations of Mack (1957) indicate that the amount of deformation to failure of very thin asphalt films is constant for a given asphalt. This finding was also confirmed by Majidzadeh and Herrin (1964) in their investigations. These conclusions were derived from tests performed at 77°F. Typical curves for tests on each of the asphalts at 77°F are shown in FIGURE 5. There is some scattering of points for thinner films but for all practical purposes, the total deformation to failure may be considered as constant. This has been attributed to the molecular attractive forces of the asphalt and to the distance molecules must be separated before rupture occurs in the film

(Mack, 1957).

The total deformation to failure versus film thickness for 50°F temperature and .004 in/min rate of extension has been plotted in FIGURE 6 for both the asphalts. The deformation to failure for film thicknesses more than 300 microns seems to be constant. But in the thinner films the deformation to failure does not appear to be constant but a function of film thickness. However, the variation is small. For the explanation of constant deformation to failure given by Mack to apply equally to the thicker films tested in this investigation, the separation between molecules must occur only in the vicinity of the failure surface. Further investigation on this aspect seems warranted.

6.5 Influence of Rate of Extension on Tensile Strength

The relationship of the rates of extension and tensile strengths for both the samples at 50°F are plotted in FIGURE 7. This plot shows the increase in tensile strength with increasing rate of extension, and is similar to results obtained by other investigators on viscous and visco-elastic materials.

6.6 Influence of Temperature on Tensile Strength

The influence of temperature on tensile strength is given in FIGURE 8, for film thickness of 300 microns and rate of extension of .004 inch per minute. The temperature and film strengths are both on a log-log scale. From the curve it is apparent that the strength of the film rises as the temperature decreases. The cohesive forces in a liquid are mainly due to the intermolecular attractions in the interior of a liquid. For a particular asphalt film with a decrease in temperature the intermolecular

attraction is increased, resulting in higher cohesive strength. Therefore, a greater force is required to rupture the asphalt film.

According to the theories discussed in Appendix A, the force necessary to break the bond between two adjacent atoms, varies inversely as the cube of the distance between the atoms. With the decrease in temperature, the molecules are brought closer together, resulting in higher tensile strength. The more the molecules are closely packed, the greater will be the strength of the asphalt.

6.7 Influence of Temperature on Unit Strain

The unit strain versus temperature relationships for the 300 micron film thickness is plotted in FIGURE 9. The unit strain at failure for both the asphalts increases as the temperature decreases.

According to the theory of potential energy advanced by Mack (1957) for the rupture of a film, the molecules must be separated a certain distance. Since molecules at lower temperatures are more closely packed, the amount of separation to cause rupture must be greater than at higher temperatures and therefore more strain is required to cause rupture.

The difference of the unit strain to failure of the two samples versus temperature is plotted in FIGURE 12. The difference is large at lower temperatures. The curve would seem to converge with the zero axis at temperatures above 77°F.

6.8 Influence of Temperature and Rate of Strain on Stiffness

The temperature-stiffness relationships are plotted in FIGURE 10, showing an increase in stiffness modulus as the temperature decreases. This relationship has been plotted for a 300 micron film thickness and

.004 in/min rate of extension. While both the unit strain to failure and the tensile strength increase with decreasing temperature, the latter increases more rapidly, resulting in a greater stiffness modulus.

The effect of the rate of strain on the stiffness modulus is shown in FIGURE 11. The stiffness modulus increases with rate of strain in both the cases.

6.9 Comparison of Tensile Properties

The investigation carried out in this project shows that the two asphalts have significantly different tensile strength characteristics. The asphalt recovered from the cracked section has higher tensile strength than that of the uncracked section, as shown in FIGURE 8. The unit strain to failure for the cracked section is much lower than that of the uncracked one, especially at lower temperatures, as shown in FIGURE 9. These results combine to produce a higher stiffness modulus for the cracked section asphalt as compared to the uncracked section, as plotted in FIGURE 10.

6.10 Application of the Results to the Cracking Problem

As discussed earlier in the thesis, the occurrence of linear transverse cracks in an asphalt pavement may be related to temperature induced strains. Therefore, materials that can take more strain to failure can resist cracking to a greater degree than those which take a lower strain to failure.

The results of this investigation show that the asphalt recovered from the cracked section takes a lower strain to failure at a higher stress level than the asphalt from the uncracked section, hence a higher stiffness

modulus. The stiffness modulus of an asphalt binder may therefore be used as an indication of the susceptibility of an asphalt pavement to transverse cracking.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 General

The objective of this investigation was to compare the fundamental tensile strength properties of two asphalts of the same penetration grade which have behaved differently in the field. This was accomplished in three phases: (i) The preliminary phase involved a fairly comprehensive literature review of tension tests on bituminous materials which is given in CHAPTER II; (ii) The design and fabrication of suitable testing equipment and (iii) A testing program to evaluate the tensile properties of the two asphalts under varying conditions of film thickness, temperature and rate of extension.

7.2 Conclusions

Based upon the literature review and the results of this investigation the following conclusions may be listed:-

1. The tensile strength of an asphalt film is a function of film thickness, temperature and rate of extension and varies as follows:
   - (i) For the same temperature and rate of extension the tensile strength increases with a decrease in film thickness.
   - (ii) For the same film thickness and rate of extension the tensile strength increases as the temperature decreases.
   - (iii) For the same film thickness and temperature, the tensile

strength increases with the rate of extension.

2. The total deformation to failure for varying film thicknesses does not seem to be a constant quantity at all temperatures. At 77°F, the total deformation may be considered as constant for all practical purposes. At 50°F it is also constant in thick films, however in thinner films, the total deformation is a function of film thickness.

3. The unit strain to failure increases as the temperature decreases, for the same rate of extension and film thickness.

4. The stiffness modulus is a function of temperature and rate of extension. For the same film thickness, this modulus increases with decreasing temperature and increasing rate of extension.

5. The stiffness modulus of an asphalt binder may be used as an indication of the susceptibility of an asphalt pavement to cracking.

7.2 Recommendations

Based upon the results of this investigation, the following recommendations may be listed.

(1) A detailed investigation of the stiffness properties of asphalts of various cracked and uncracked areas should be undertaken and limiting values of stiffness modulii at lower temperatures for better performance, should be established.

(2) Tension tests on asphalt aggregate mixtures should be performed and correlated with those on asphalt films.

(3) Since the deformation measuring device had a non-linear calibration scale, it was somewhat cumbersome to use. Therefore, a device having a linear scale for the measurement of deformation should be developed.

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APPENDIX A

THEORY OF POTENTIAL ENERGY AND CAVITIES

AND

HYDRODYNAMIC THEORY

- General
- Theory of Potential Energy and Cavities
- Limitation of Theory
- Hydrodynamic Theory
- Discussion of the Theories

A.1 General

A number of variables have been listed in CHAPTER II which may influence the strength of an asphalt film. Asphalt being a viscoelastic material, viscosity, rate of extension and film thickness may be considered to mainly influence the strength,

$$\sigma = f\left(n, \frac{dh}{dt}, h\right)$$

where	σ	= tensile strength	(MLT^{-2})
	n	= viscosity	$(ML^{-1}T^{-1})$
	dh/dt	= rate of extension	(LT^{-1})
and	h	= film thickness	(L)

The dimensional analysis of the above quantities shows the following relationship

$$\sigma = \phi\left(\frac{u}{h}, \frac{dh}{dt}\right)$$

Thus the film strength will vary directly as the viscosity and rate of extension and inversely as the film thickness. However, cavitation does reduce the final strength. The effect of cavitation has been considered while developing the following formulas.

A.2 Theory of Potential Energy and Cavities

The theory of potential energy was advanced by C. Mack (1957) to explain the strength of thin films of asphalt in pure tension. The rupture of thin film occurs in the film itself and therefore, film strength is partly a function of the secondary valence forces between adjacent asphalt molecules. Since asphalts contain polar and non-polar compounds,

the attractive forces are mainly due to induction and dispersion forces. The energies associated with these forces both decrease with the sixth power of the distance between the molecules and therefore as suggested by Mack, may be expressed by the Lennard-Jones equation.

$$\varphi(\gamma) = \frac{A}{\gamma^m} - \frac{B}{\gamma^n} \quad \ldots\ldots\ldots\ldots \quad (1)$$

Where $\varphi(\gamma)$ is the potential energy between two adjacent atoms separated by a distance γ and A, B, m and n are constants. The expression $A/_{\gamma}m$, represents the potential energy due to repulsive forces and the $B/_{\gamma}n$, the potential due to the attractive forces. Tensile rupture however, occurs in the material when the applied force equals the maximum force due to the potential of the secondary bonds. The rupture occurs during the stretching of a film when the distance of the molecules has reached a certain value. The potential energy increases with increasing distance of the molecules. The increase in distance at rupture or the strain, depends upon the original degree of packing of the molecules and their potential energy. It is greatest when the molecules are closely packed or in positions of low potential energy and decreases with looser packing and greater potential energy. In other words, materials with closely packed molecules have higher theoretical tensile strength than those with loosely packed molecules. The force necessary to break the bond, according to Boer (1936) can be written as

$$\sigma_m = \frac{C}{\gamma_m 3} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where C is a constant, γ is the distance between atoms, and σ_m is the tensile force. This theoretical strength is very much affected by the cavities and orientation of molecules. Presence of cavities decreases the

theoretical value σ_m and varies with the number of cavities. Since cavities are associated with the increase in volume in the direction of pull or in other words to the tensile strain, it can be said that the film thickness influences the observed breaking stress. In addition, the change in the orientation of the molecules at different film thicknesses influences the strength-thickness relationship. However, this cannot be determined exactly as the chemical structure and the degree of orientation of the molecules in a film are not known.

According to deductions of Mack (1957), the tensile strength of a film can be expressed by the equation

$$\epsilon = \left(\frac{A}{\sigma}\right)^{\frac{1}{a}}$$

$$\text{or} \quad \frac{\Delta h}{h} = \left(\frac{A}{\sigma}\right)^{\frac{1}{a}}$$

$$\text{or} \quad \sigma = A\left(\frac{h}{h}\right)^{-a} \qquad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where ϵ is the strain corresponding to stress σ, and Δh is the amount of deformation to failure. Since the rupture occurs when the molecules are separated by a certain distance, it is assumed that Δh is a constant for a given asphalt

σ = tensile strength

h = film thickness

A = a constant related to rheological properties of asphalt

a = a constant related to composition and type of asphalt

From equation (4), it may be further derived that

$$\frac{\sigma}{\sigma_m} = \left(\frac{hm}{h}\right)^a \qquad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

where σ_m and hm represent the maximum film strength and h_m the optimum film thickness. The values of 'a' are positive when $h < h_m$, and negative when $h > h_m$. In the region where the values of 'a' are positive, the secondary bond forces are strong and probably cause orientation of the molecules, whereas for the negative region, they diminish with increasing film thickness. Thus the constant 'a' can be considered as also a measure of the degree of packing of molecules in the film. As reported by Mack, 'a' varies from 1.484 for coal tar to 0.253 for Venezuelan Oxidized asphalt and optimum film thickness varied from 25.8 microns to 51.4 microns for the materials tested.

A.2.1 Limitation of Theory

According to the derivations of Mack, the film thickness considerably influences the tensile strength of asphalt films. It is applicable only when no flow occurs in the asphalt. As observed during the tests, there is no flow of asphalt in very thin films and material may be considered to be subjected only to the tensile stresses. But in thicker films, the rupture occurs due to radial and axial flow of the material and therefore, this theory cannot be applied for thicker films.

A.3.1 Hydrodynamic Theory

This is one of the earliest theories developed to explain the behaviour of materials in thin films. In many articles appearing in the literature, it has been named as theories of "restraint of deformation" or reduction of plastic flow, but essentially they are the same as hydrodynamic theory. It is credited to the theoretical and experimental works of J. Stephan.

It considers the flow behaviour of thin layers of viscous materials, sandwiched between two parallel plates and subjected to a pull. It is found that the force necessary to separate the plates is a function of the thickness of the material. As the film thickness decreases, a greater force is required to deform the material to a certain value.

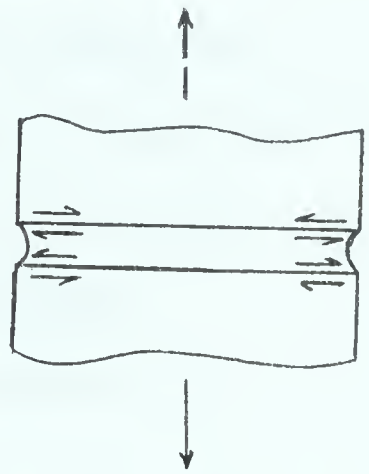


FIGURE A.1 FORCES ACTING ON THE FILM.

Consider two circular, plane-parallel, solid plates with a liquid filling the clearance between the plates. When the plates are pulled apart in the direction of the arrow the liquid flows towards the axis of the system from the bulges shown in the FIGURE A.1. in addition to deforming in the direction of the applied stress. To maintain this movement in a viscous liquid, a stress has to be continually operative which brings about the rupture of the film. Thus the rupture occurs due to shear. Further, since the inward movement of the material in contact with the two plates is prevented, the theory assumes that the flow at any other plane is a parabolic function of the distance between the two plates. Therefore, the linear velocity of the flow, which is a parabilic function of the film thickness is considerably smaller in the thinner films.

Stefen measured the force necessary to separate two circular

glass discs immersed in a liquid at a given rate and expressed the derivation of this theory in complex mathematical form which was later simplified by Bikerman (1960). It is expressed, for complete immersion, by the equation,

$$F = \frac{3n\pi R^4}{2h^3} \cdot \frac{dh}{dt} \quad \ldots\ldots\ldots\ldots \quad (5)$$

where F = applied tensile pull

n = viscosity of Newtonian liquid

R = radius of the plate

h = film thickness

and, for no immersion, by the equation

$$F = \frac{3\ V^2\ n}{2\ \pi\ H^5} \cdot \frac{dh}{dt} \quad \ldots\ldots\ldots\ldots \quad (6)$$

where V = volume of the material confined between two parallel plates.

The flow properties of non-Newtonian liquids can be expressed by the equation

$$\dot{\gamma} = \tau^n/K \quad \ldots\ldots\ldots\ldots \quad (7)$$

where $\dot{\gamma}$ = rate of shear

τ = shear stress

n = a constant of the material and
= 1 for Newtonian liquids

and K = is related to the viscosity of the material and equal to viscosity for Newtonian liquids (at testing temperature)

A suitable formula suggested by Scott (1931) for the tensile forces for these materials can be expressed by equation

$$F^n = \frac{dh}{dt} \cdot \frac{(2n)^n \cdot K \cdot (n+2) \cdot V \frac{3n+1}{2}}{(3n+1)^n \cdot \pi \frac{n+1}{2} \cdot H^{\frac{5n+5}{2}}} \quad \ldots \quad (8)$$

where dh/dt = rate of extension.

For constant rate of extension,

$$H = H_o + t\delta \quad \ldots \quad (9)$$

where H_o = initial thickness of material

δ = rate of extension

t = time of testing in seconds

δt = h, the amount of deformation in t seconds of testing

Therefore, given the time of testing t, the tensile force acting on the material can be easily obtained.

It is observed that the film strength is inversely related to the film thickness in the equation (8) and that it depends upon the type of material, viscosity and rate of loading.

A.3.2. Limitations of Theory

The horizontal flow of the material between two parallel plates during tension test occurs as a result of pressure difference between the peripheral and central portions of the material (Bikerman, 1960). The theory assumes that this pressure difference cannot be relieved in any other way. However, if the pressure difference is relieved by presence of air channels or cavities, or due to formation of numerous filaments, the theory is no longer valid.

Another limitation of the theory is Stefan's assumption that the materials flow laminarly and give way in shear at a slow rate of loading.

But it is observed that the materials rupture without appreciable flow in a fast rate of loading. In such cases, the rupture of the film indicates that the failure is primarily due to tensile stress rather than shear flow alone.

A.4. Discussion of the Theories

The theory of potential energy and cavities is derived from the concept of secondary valence forces between the adjacent molecules. According to the basic assumptions, it is applicable to cases in which there is no flow in the asphalt. This phenomena is observed only in very thin films where the flow is restrained and the material is subjected to the tensile stresses only and therefore, is applicable to very thin films only. Moreover, it is also assumed that the amount of deformation to failure (Δh) is a constant and depends upon the type of asphalt. Asphalts with higher degree of aromaticity can take greater strain to failure. Mack (1957) has also stated that if the time of loading is more than 100 seconds, rate of loading has practically no effect on the film strength.

The theory of hydrodynamics, is based upon the assumption that there is a radial flow of the material placed between two parallel plates, as the plates are pulled apart. This radial flow is due to pressure difference built up in the material and it is assumed that the pressure difference is not relieved. Further the strength of the film is influenced by the thickness of the film, viscosity and rate of loading and thereby influences the applicability of this theory.

At very thin films, it is observed that there is no radial flow of the material and there is formation of a number of filaments or cavities

indicating that the rupture of the film is due to tensile stresses, rather than shear flow.

The higher the viscosity of the material, the higher is the resistance to deformation and flow and therefore more energy is needed to break the films. Bikerman (1960) states that for higher viscosities, say 1000 gm/cm.sec., the fracture is almost solid fracture or due to elastic failure. For materials of intermediate range viscosities, i.e., when the viscosity is not so great as to cause a solid fracture nor so small as to give rise to a uniform liquid flow, the material flows towards many points spread all over the film. At further separation of the plates, filaments or threads start from these points. Thus in such cases, the failure is primarily due to tensile stresses and this theory is no longer valid.

The rate of loading has the same influence as the viscosity. The greater the rate of loading, the greater is the viscous resistance. At fast rate of loadings, there is more a tendency to fail in tension than by shear flow.

Thus it is concluded that there is not one theory which can be applied to the entire range of testing. For thicker films, the hydrodynamic theory is suitable whereas for thinner films, the theory of potential energy and cavities appears to be more suitable.

APPENDIX B

DESCRIPTION AND CALIBRATION OF TESTING EQUIPMENT

- Tension Testing Machine
- Load Cell
- Test Blocks
- Film Forming Device
- Thermocouple
- Displacement Transducer

B.1 Tension Testing Machine

A compression testing machine, 5 ton capacity, Model 57 of Wykeham Farrance Engineering Ltd. was run in reverse for applying load at constant rate of extension. The machine has a capacity to run at speed ranges of .075 to .000045 in/min. Special fittings as shown in FIGURE B.1 for the top and bottom heads of the machine were designed and fabricated. The steel ball at the top fixed head is provided to give flexibility and ability to adjust itself to proper alignment. The rods connecting the top and bottom heads have spherical surfaces to further facilitate self alignment.

B.2 Load Cell

It consists of a thin walled aluminium cell of 1 inch external diameter, 2 inch long, with 3/8" x 1/4" cappings on either ends. The thickness of the wall is .075 inch and is designed to give a strain of one microinch for two pounds load and carry a maximum load of 2000 pounds. The load cell is shown in FIGURE B.2 and the design given below.

B.2.1 Design of Load Cell

Assumptions: Tensile Strength = 13,000 psi

Modulus of elasticity = 10×10^6 psi

Poisson's Ratio = 0.33

Taking, load P = 2 pounds, Extension x = 10^{-6} in.

and 1 = 1 inch (gauge length for electrical resistance)

$$E = \frac{\text{Stress}}{\text{Strain}} = \frac{P/A}{x/L} = \frac{Pl}{x.A}$$

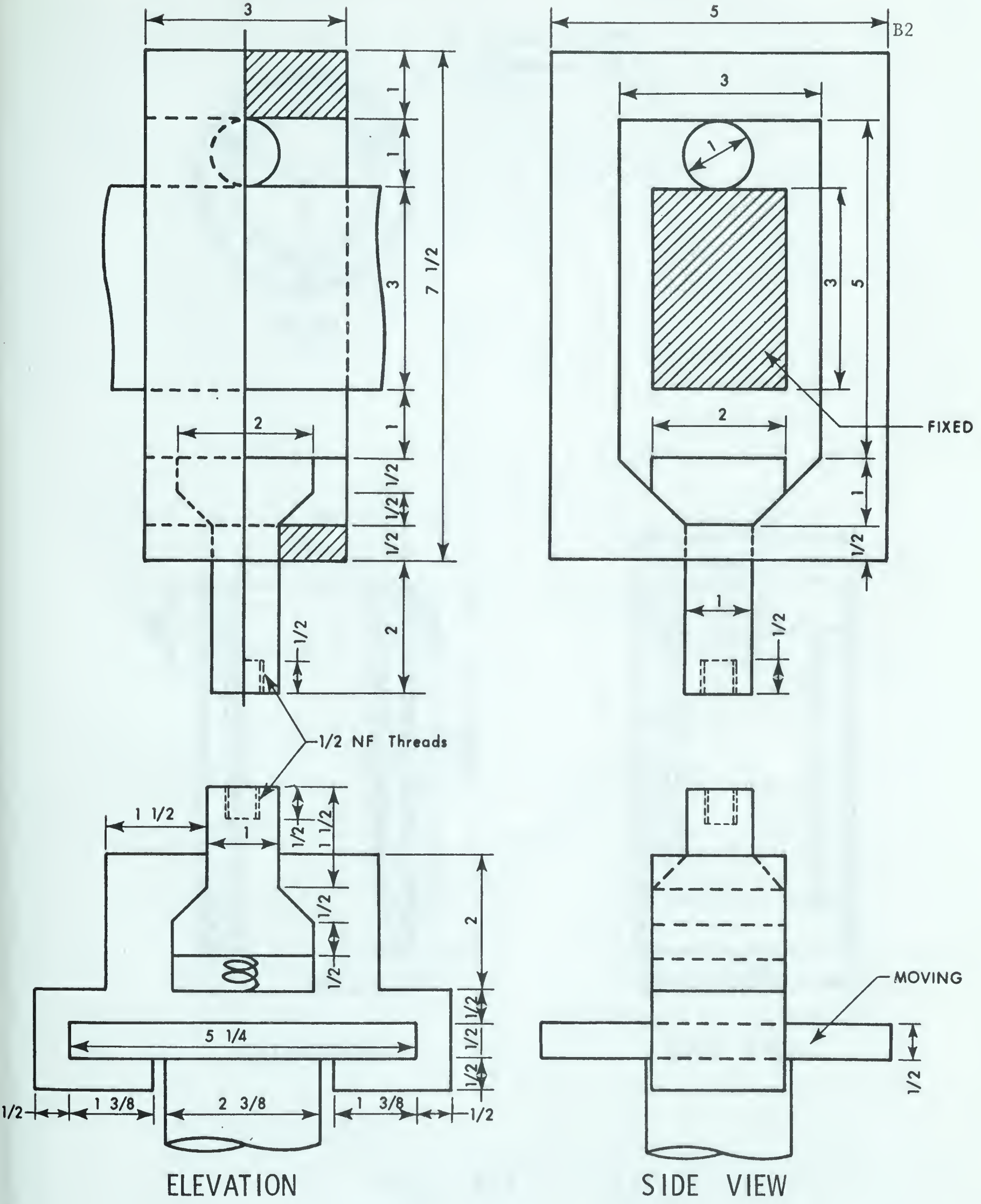
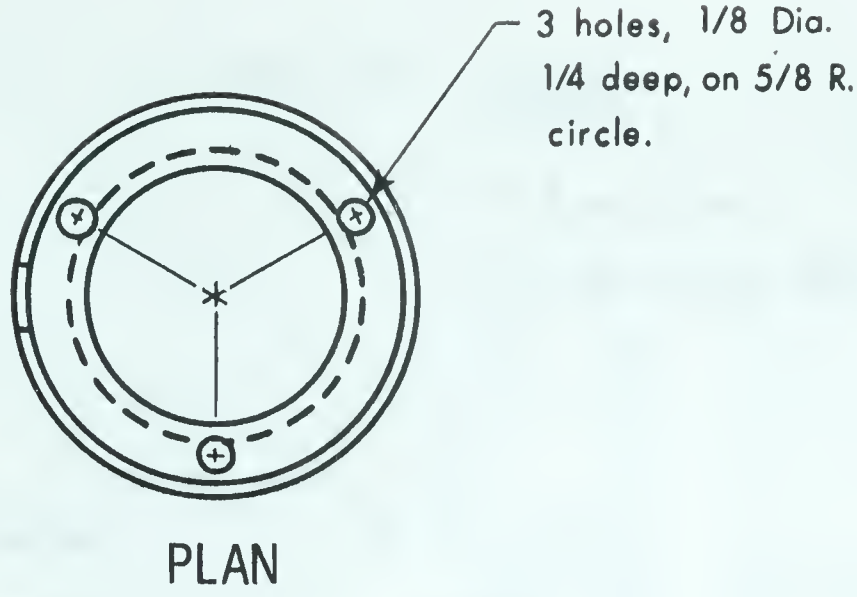
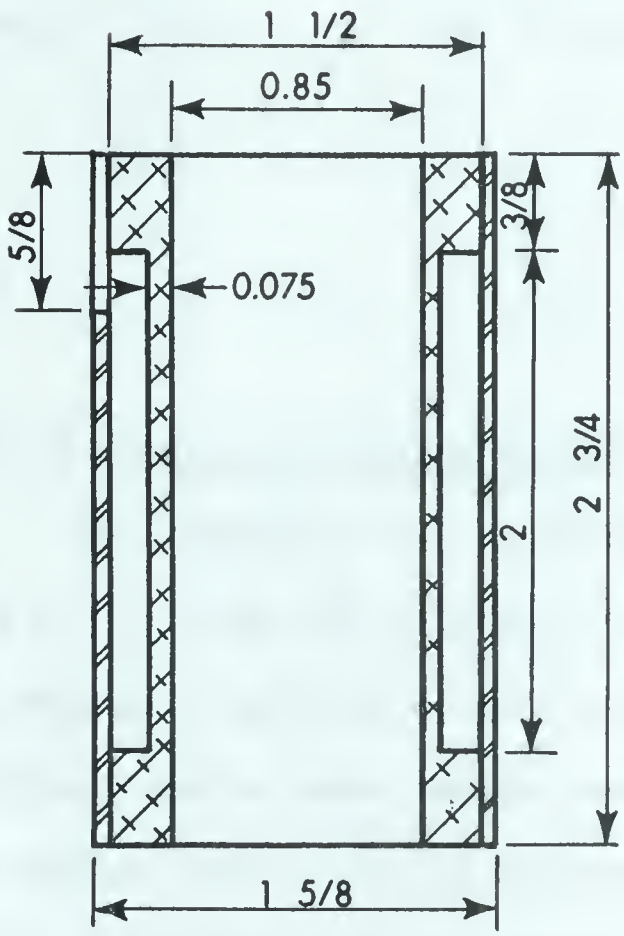


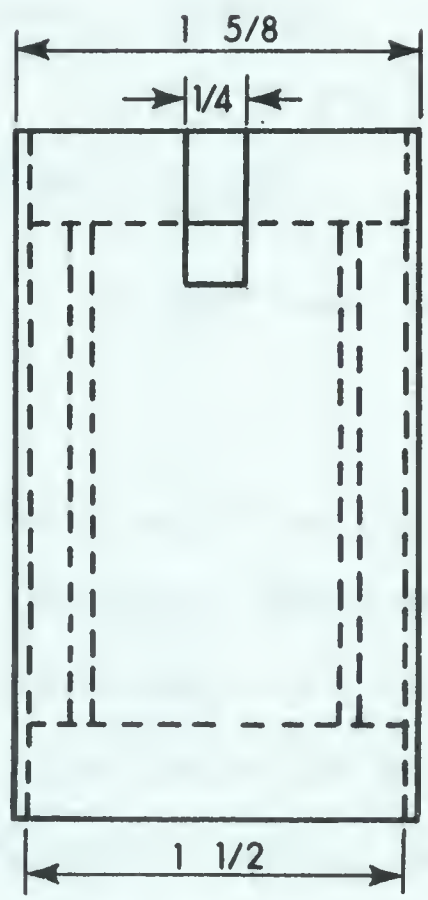
Fig. B1 - HEAD ATTACHMENTS FOR TENSION TESTING



PLAN



ELEVATION



SIDE VIEW

Fig. B 2 - LOAD CELL

$$10 \times 10^6 = \frac{2 \times 1}{10^{-6} \times A}$$

Therefore, $A = 0.2$ sq. inch

$A = \frac{\pi}{4}(D^2 - d^2)$, where D = external diameter

d = internal diameter

External radius $R = 1$ inch

Internal radius $= \sqrt{D^2 - 4\frac{A}{\pi}} = \sqrt{1 - \frac{0.2 \times 4}{\pi}} = \sqrt{1 - .255}$

$= \sqrt{.745} = .85$ inch

and wall thickness $t = \frac{D}{2} - \frac{d}{2} = \frac{1 - .85}{2} = .075$ inch

Now, when $P = 2000$ pounds, stress $= \underline{2000/0.2}$

$= 10{,}000$ psi (safe)

strain $= \frac{10{,}000}{10 \times 10^6}$

$= 10^{-3}$ inch (safe)

B.2.2 Electrical Strain Gauges

The diagram of the electrical bridge circuit mounted on the surface of the load cell is given in FIGURE B.3. The strain gauges were of 120 ohms each and the constant source of D.C. power supply at 3 volts was obtained from a power source connected to the main line of 110 volts, 60 c/s supply. The bridge is balanced for any temperature change. The output of the bridge with the change of resistance, when the strain is applied to the load cell, is in millivolts.

B.2.3 Acromag Amplifier

The electrical circuit diagram is given in FIGURE B.4 and photograph

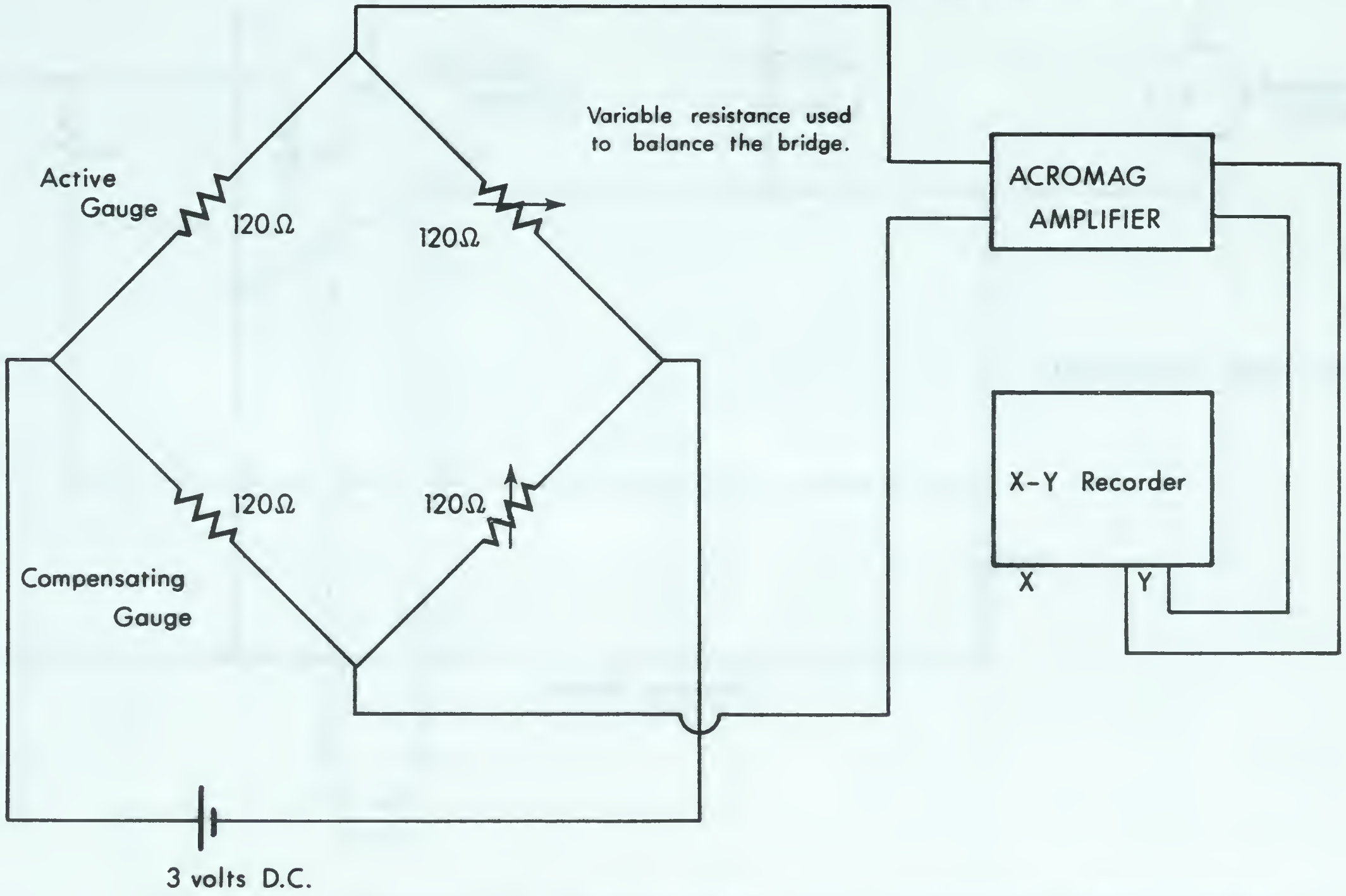


Fig. B 3 - BRIDGE CIRCUIT DIAGRAM

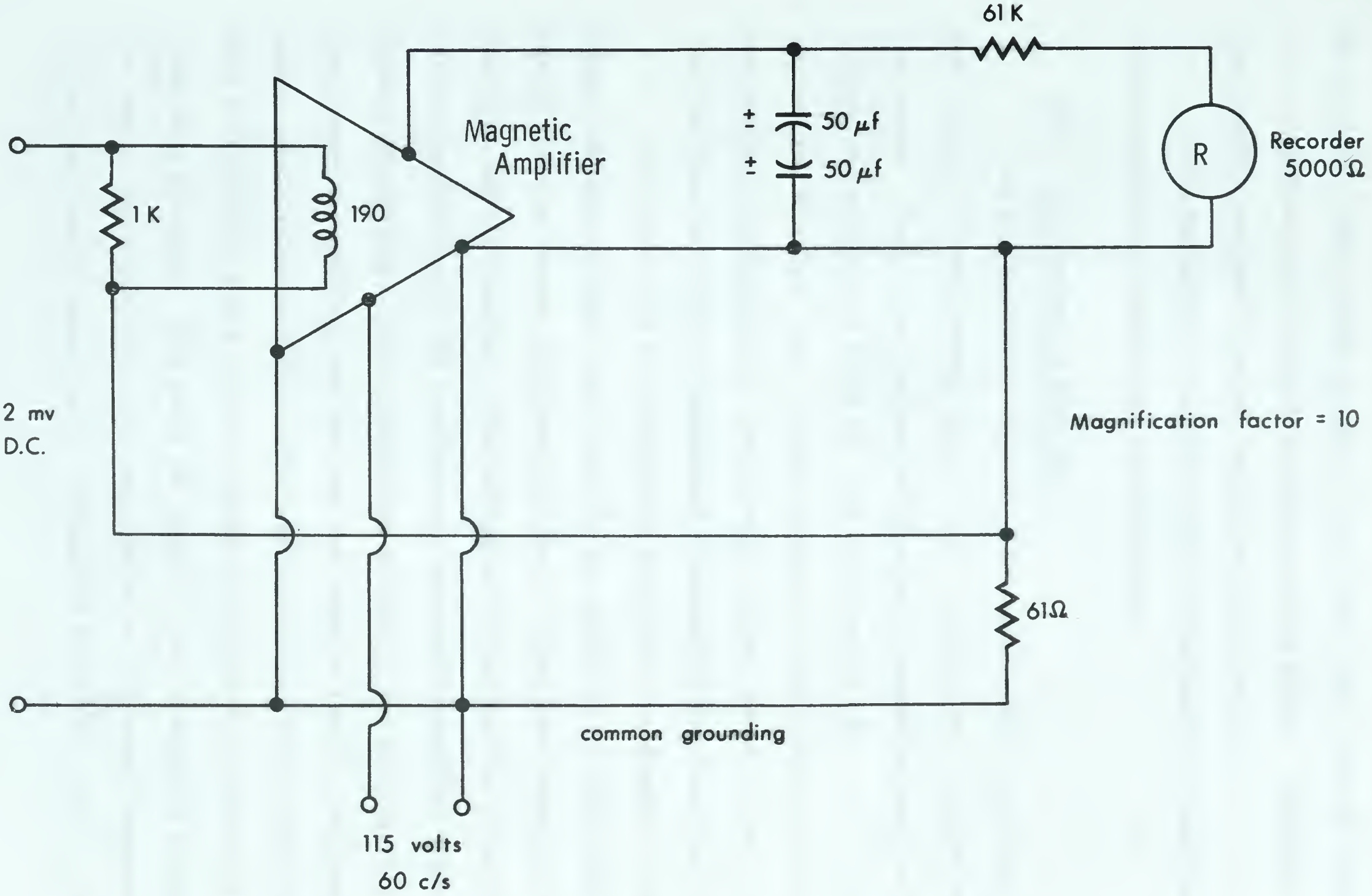


Fig. B 4 - SCHEMATIC DIAGRAM OF THE ACROMAG AMPLIFIER

in Plate 5A. This proved to give a very steady output with no noticeable drift with time, even during the slowest testing period. Therefore, the load results obtained from this set-up are fully reliable.

The commercially available parts of the amplifier were assembled in the Electronics Workshop of the University.

B.2.4 Calibration of Load Cell

The calibration of the load cell was done with a proving ring. The fittings for the proving ring to work in tension was designed and fabricated. The proving ring was calibrated by suspending weights from a lever arm as shown in Plate 4B. The lever arm is 1/2" x 2" in cross-section and 30 inches long. It was designed and fabricated to work with the tension testing machine. The proving ring was connected at 6 inches from the fulcrum. Thus the mechanical advantage of the lever was 1 to 5.

The load cell and the proving ring were then mounted on the Tension Testing Machine. The load cell was subjected to 500 pounds load for 10 times to remove all hysterisis loss. It was then connected to the amplifier and the recorder. The deflection of the recorder's pen for various sensitivity of the recorder were observed by applying strain through the machine. The corresponding reading of the proving ring dial gauge were also observed and the load was computed from its calibration curve. These loads were then marked against the recorder's deflections. Thus a Calibration Scale for the recorder for different sensitivity and loads were obtained. This scale was used for load evaluation throughout the tests. The Calibration Scale was checked at different temperatures of test and found to agree well. The maximum sensitivity was 1" = 20 lbs.

B.3 Test Blocks

They consist of 1 inch diameter and 1/2 inch high stainless steel blocks, AISI no. 431, weighing about 47 grams each and hardened to take a better polish. The top and bottom faces of the blocks were finished and parallel to less than .0005 inch. The surface on which the asphalts were to be placed were lapped to ASA finish symbol (✓4) i.e. the average roughness of the surface was about 4 microinches or approximately 0.1 micron.

The test blocks were connected to the top and bottom rods after film formation, by three screws which were tested in tension to take approximately a load of 5000 pounds. Further details of the test blocks are given in FIGURE B.5.

B.4 Film Forming Device

Hallikainen Instruments Film Former, Model 1147 was used for forming films of various thicknesses. It consists of a base with a flat ground surface on to which is placed an adjustable weight with a ground surface. The photograph is given in Plate 1A. Two brass rings shown in FIGURE B.5 were used to prevent the lateral movement of the test blocks during film formation. The adjustable weight was 1-3/4 inches in diameter, 5 inches long and weighed 3.3 pounds. The film former is made of stainless steel.

B.5 Thermocouple

Two thermocouples were made by connecting copper and constantan wires together. The junctions were heated to fusion to obtain firm contact between the two wires. They were then connected in series to get higher potential difference at various temperatures of test. The connection

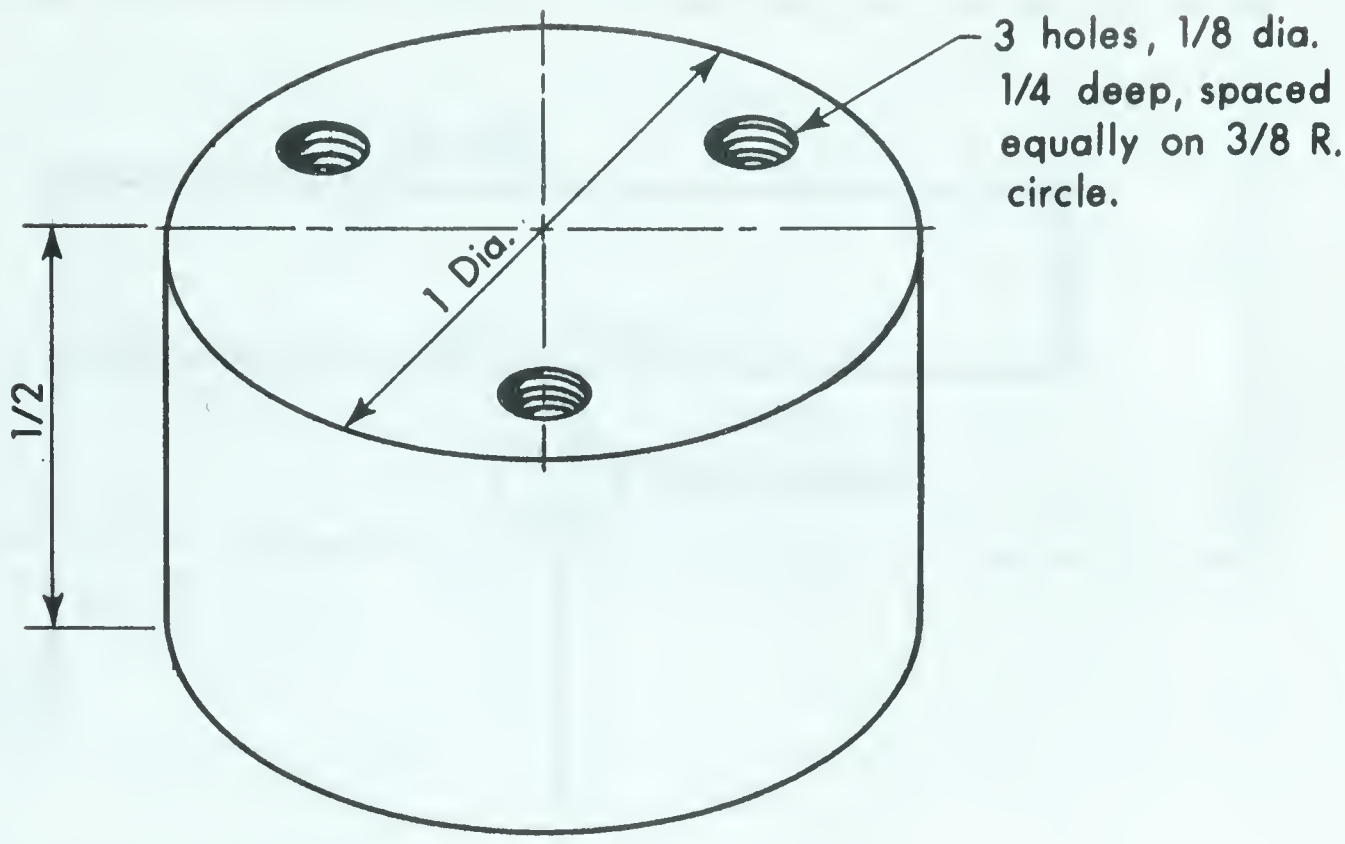


Fig. B5A -TEST BLOCK

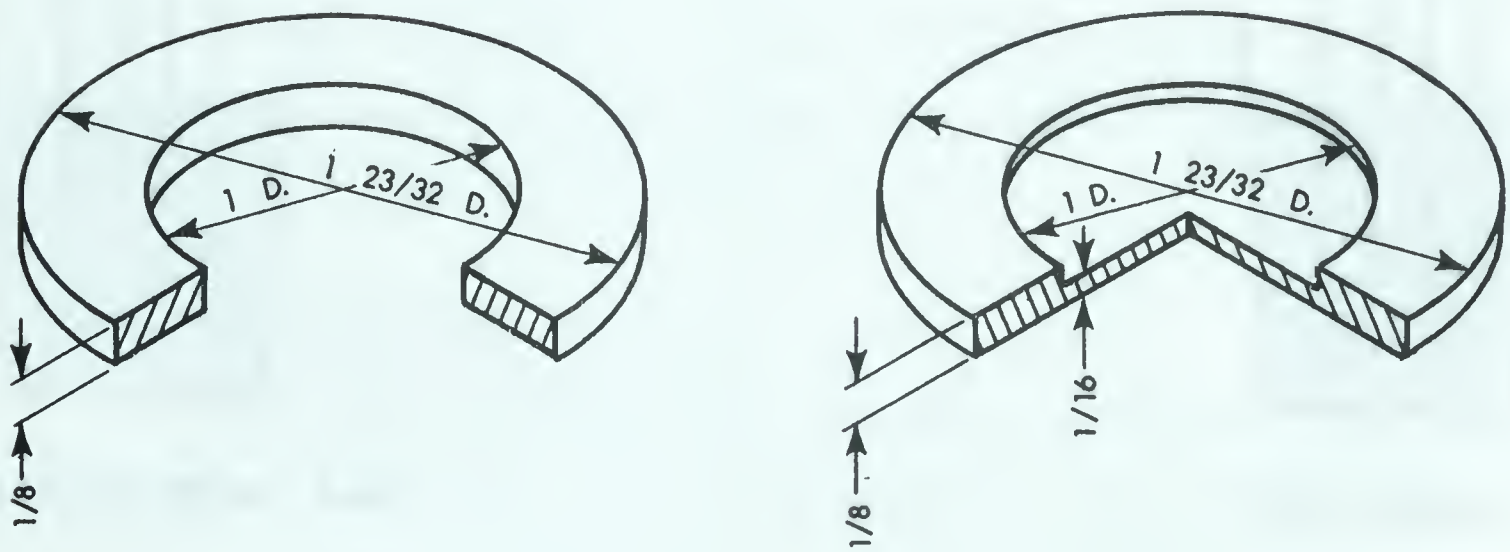


Fig. B5B - TEST BLOCK GUIDES

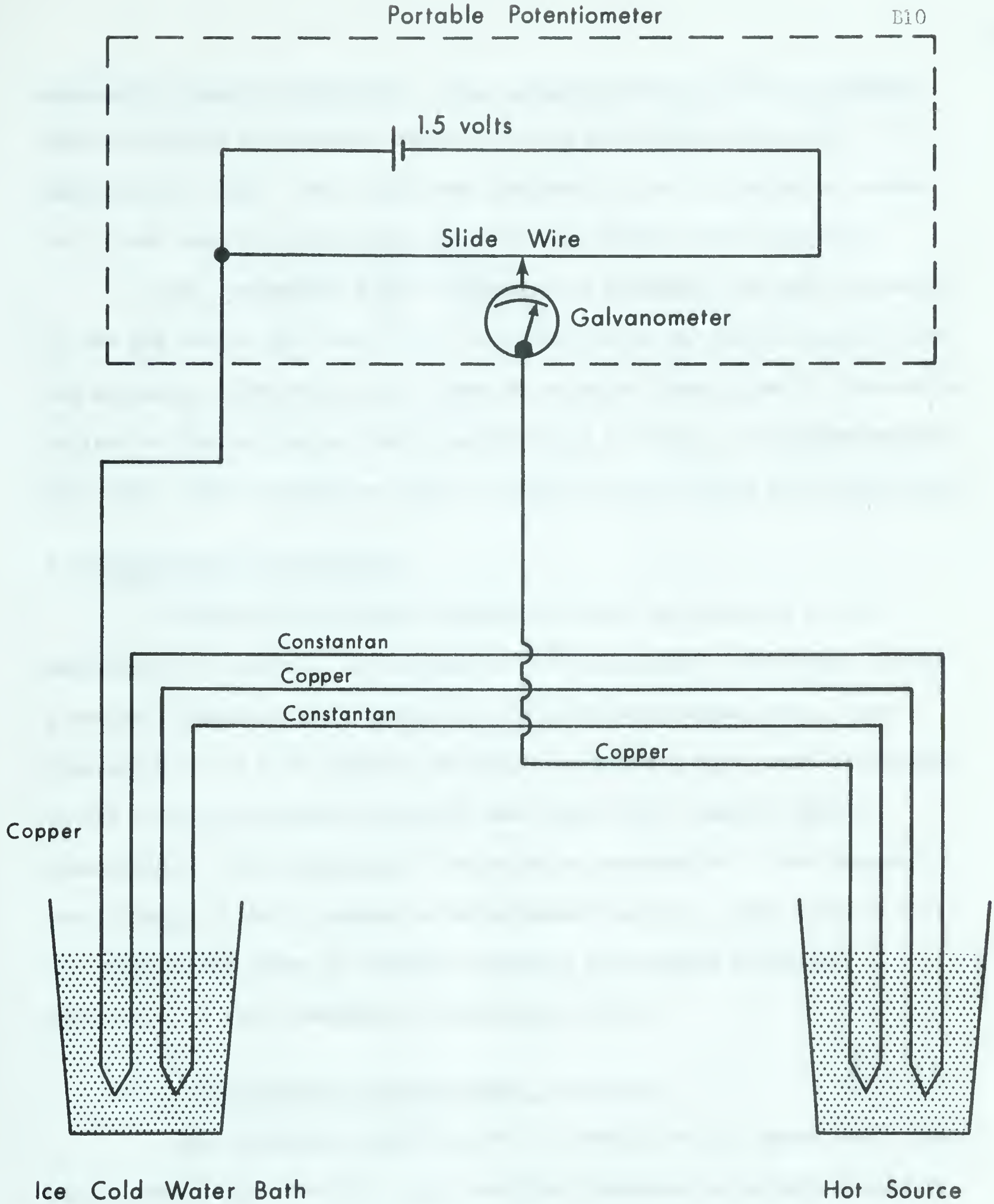


Fig. B 6 - SCHEMATIC DIAGRAM OF POTENTIOMETER AND THERMOCOUPLE

diagram is given in FIGURE B.6. The potential difference was measured with a portable type potentiometer of Leeds and Northrup Co. Ltd., Catalogue no. 8867. One couple was immersed in ice cooled water stored in a flask and the other glued near the test blocks with epoxy glue.

The thermocouple was calibrated by immersing the end, connected to the top rod of the test block, in a water bath at various temperatures. The potential differences were found to be twice those given in Conversion Tables for thermocouples, Leeds and Northrup Company, as two thermocouples were used. This Conversion Table was used for evaluating all temperatures.

B.6.1 Displacement Transducer

Sanborn Displacement Transducer Model 580 was used for the measurement of strain. It consists of a differential transformer having a moveable magnetic core, cased in a well-shielded pickup head. One-thousandth of an inch movement of this core gives a full-scale deflection on the associated Sanborn Recorder when used with a Sanborn Carrier Preamplifier. The displacement measured is transferred to the magnetic core through a spring-loaded carbide-tipped stainless steel contact rod. The contact rod rides in jewelled bearings for minimum friction. A photograph of the transducer is given in Plate 2B.

B.6.2 Calibration of Displacement Transducer

The calibration was done with a sensitive dial gauge which reads up to .0001 inch. The dial gauge and the transducer were both placed in contact with the lower moving head of the machine. The head was moved by operating the hand wheel of the machine. The deflections on the recorder's X-axis corresponding to the dial gauge readings were marked and

a calibration scale obtained. This scale was used for the measurement of extension of the sample. The maximum sensitivity was 1" = 10 x 10^{-4} inch.

B.6.3 Extension of the Apparatus

A solid steel block 1 inch diameter and 1 inch long, comprising the dimensions of the test blocks was mounted on the machine. The hand wheel was operated and the deflection on the X-axis of the recorder corresponding to the loads on the load cell was marked. This gave the extension of the apparatus at various loads on the sample. The extension of the apparatus was deducted from the total extension during each test, to evaluate the extension of the asphalt sample.

APPENDIX C

SAMPLE CALCULATION AND ERRORS

- Calculation of Film Thickness
- Calculation of Tensile Stress
- Calculation of Tensile Strain
- Calculation of Stiffness Modulus
- Errors Due to Roughness of Steel Surface
- Errors due to Temperature Difference in the Calculated Film Thickness
- Errors due to Non-parallelism

C.1 Calculation of Film Thickness

Diameter of test blocks, $d = 1 \text{ inch} = 2.54 \text{ cm.}$

Area of test blocks, $A = \frac{\pi}{4} (2.54)^2 = 5.06 \text{ sq.cm.}$

Assuming, specific gravity of asphalt = 1.00

Volume of asphalt, $Va = \frac{\text{Weight of asphalt}}{\text{Specific weight of asphalt}}$

$= W$ in C.G.S. Units.

$$\text{Film thickness} = \frac{\text{Volume of asphalt}}{\text{Area of the test block}} = \frac{V}{A}$$

$$= \frac{W}{5.06} \text{ Cm} = .2 \text{ W Cm}$$

$$= 2 \times 10^3 \text{ W. microns.}$$

Taking sample no. 1, 40°F, .004 in/min rate of extension for asphalt 242

$$\text{Film thickness} = 2 \times 10^3 \times .078 = 156 \text{ microns}$$

C.2 Calculation of Tensile Stress

$$\text{Tensile stress} = \frac{\text{Load in pounds (P)}}{\text{Area of asphalt in sq. inch}}$$

$$= \frac{P}{\frac{\pi}{4}(1)^2} \text{ psi} = \frac{P}{.785} \text{ psi}$$

Taking the same sample as of C.1.

$$\text{Tensile stress} = \frac{235}{.785} = 299.36 \text{ psi}$$

C.3 Calculation of Tensile Strain

$$\text{Tensile Strain} = \frac{\text{Extension in microns}}{\text{Film Thickness in microns}}$$

Taking the same sample, $\text{Strain} = \frac{110 \times 10^{-4}}{156 \times 40 \times 10^{-6}} = 1.763$

C.4 Calculation of Stiffness Modulus

$$\text{Stiffness Modulus} = \frac{\text{Tensile Strength}}{\text{Tensile Strain}}$$

$$= \frac{299.36 \text{ psi}}{1.763}$$

$$= 169.80 \text{ psi}$$

C.5 Errors due to Roughness of Steel Surface

The surfaces were polished to a maximum of 4 microinches which is approximately 0.1 micron. Therefore the errors in the film thicknesses, taking both the blocks together

$$= \text{Calculated film thickness} \pm 0.2 \text{ microns}.$$

C.6 Errors due to Temperature Difference in the Calculated Film Thickness

Assuming coefficient of cubical expansion of bitumen

$$= 60 \times 10^{-5} \text{ per degree centigrade}$$

$$= 35 \times 10^{-5} \text{ per degree } °F.$$

$$= 35 \times 10^{-5} \text{ micron/micron/}°F.$$

The coefficient of linear expansion

$$= 12 \times 10^{-5} \text{ micron/micron/}°F, \text{ approximately}$$

Taking thickest film of 1000 microns and maximum drop of temperature 40°F, the total change in film thickness

$$= 1000 \times 40 \times 12 \times 10^{-5} \text{ microns}$$

$$= 4.8 \text{ microns}$$

$$= 0.4\%, \text{ a very insignificant amount.}$$

C.7 Errors due to Non-parallelism

It was difficult to measure the non-parallelism of the faces of the asphalt films. Every precaution was taken to keep it to the minimum. The parallelism of the faces of each test block were tested with a very sensitive dial gauge, reading .0001 inch per division. The pairs were placed on a smooth flat surface with the dial gauge in contact with the top most face, and moved around such that the total surface of the face gradually came in contact with the dial gauge. There was practically no drift of the needle of the dial gauge.

The parallelism of the film forming device was also difficult to check. However, it is known that this device generally produced uniform films for sliding plate microviscometer tests. It was, therefore, assumed that the films formed during this investigation were of uniform thickness within reasonable limits.

APPENDIX D

SUMMARY DATA SHEETS

UNIVERSITY OF ALBERTA
ASPHALT LABORATORY
TENSION TEST ON ASPHALT FILMS

Diameter of Test Blocks - 1 inch
Specific Gravity of Asphalt = 1.0
Temperature - 77°F

Rate of Extension - .004 in/min.

Asphalt Type	No. of test	Wt. of test blocks & asphalt (gms)	Wt. of test blocks (gms)	Wt. of asphalt (gms)	Film thickness microns	Load at failure lbs	Stress at failure psi	Corrected Extension at failure 10^{-4} in	Strain at failure	Stiffness Modulus psi	Type of failure
No. 224	1	845	821	.024	48	20.5	26.11	5	.26	100.4	Brittle
	2	806	783	.023	46	21.0	26.75	7	.38	70.39	Brittle
	3	920	841	.089	168	18.0	22.90	9	.134	170.9	Numerous bulbs
	4	1.039	759	.280	560	10.0	12.74	6	.0267	477	Plastic
	5	445	438	.007	14	21.5	27.38	7	1.25	21.90	Brittle
	6	933	887	.046	92	18.5	23.55	8	.216	109.03	Numerous bulbs
	7	916	841	.175	350	21.0	26.75	12	.0950	312.6	Plastic
No. 242	1	774	766	.008	16	22.5	28.66	5	.781	36.69	Brittle
	2	804	782	.022	44	21.5	27.38	5	.284	96.4	Brittle
	3	861	821	.040	80	21.0	26.75	12	.375	71.33	Numerous bulbs
	4	835	780	.055	110	19.0	22.35	9	.2045	109.29	Plastic
	5	980	783	.197	384	8.5	10.83	12	.0775	139.7	Plastic
	6	905	887	.018	36	21.5	27.38	7	.572	47.86	Brittle
	7	870	841	.029	58	21.0	26.75	11	.474	56.43	Brittle
	8	771	766	.005	10	24.0	30.57	7	1.75	17.47	Brittle

UNIVERSITY OF ALBERTA
ASPHALT LABORATORY
TENSION TEST ON ASPHALT FILMS

Diameter of Test Blocks - 1 inch
Specific Gravity of Asphalt = 1.0
Temperature - 50°F

Rate of extension - .004 in/min.

Asphalt Type	No. of test	Wt. of test blocks & asphalt (gms)	Wt. of test blocks (gms)	Wt. of asphalt (gms)	Film thickness microns	Load at failure lbs	Stress at failure psi	Corrected Extension at failure 10^{-4} in	Strain at failure	Stiffness Modulus psi	Type of failure
	1	974	886	.088	176	300	382.16	36	.511	747.86	Brittle
	2	840	754	.086	172	363	462.42	35	.5087	909.36	Brittle
	3	975	745	.230	460	35	44.58	27	.1465	304.3	Plastic
No. 224	4	813	438	.375	750	26	33.12	26	.0865	382.8	Plastic
	5	862	745	.117	234	150	191.08	41	.4375	436.75	Plastic
	6	573	438	.135	270	114	145.22	36	.3325	436.75	Plastic
	1	872	782	.090	180	102	129.93	42	.5825	223.05	Brittle
	2	1.028	821	.207	414	28	35.67	48	.2894	123.25	Plastic
	3	1.110	784	.326	652	21	26.75	54	.2050	130.48	Plastic
No. 242	4	860	788	.072	144	160	203.82	34	.590	345.45	Brittle
	5	915	846	.069	138	210	267.51	36	.6520	410.20	Brittle
	6	1.124	749	.375	750	21	26.75	37	.1233	216.95	Plastic
	7	906	766	.140	280	53.5	68.15	50	.4465	152.63	Plastic

UNIVERSITY OF ALBERTA
ASPHALT LABORATORY
TENSION TEST ON ASPHALT FILMS

Diameter of Test Blocks - 1 inch
Specific Gravity of Asphalt = 1.0
Temperature - 40°F

Rate of extension - .004 in/min.

Asphalt Type	No. of test	Wt. of test blocks & asphalt (gms)	Wt. of test blocks (gms)	Wt. of asphalt (gms)	Film thickness microns	Load at failure lbs	Stress at failure psi	Corrected Extension at failure 10^{-4} in	Strain at failure	Stiffness Modulus psi	Type of failure
No. 224	1	954	890	,064	266	350	445.85	85	.7987	558.2	Brittle
	2	977	844	.133	362	258	328.66	105	.7249	453.38	Numerous bulbs
	3	938	757	.181	536	200	254.77	105	.4875	522.60	Numerous bulbs
	4	1.015	747	.268	730	170	216.56	90	.3082	702.66	Numerous bulbs
	5	806	441	.365	910	150	191.08	80	.2197	869.73	Plastic
No. 242	1	844	766	.078	156	235	299.36	110	1.763	169.8	Brittle
	2	1.072	784	.288	576	35	44.58	137	.5945	74.98	Numerous bulbs
	3	954	824	.130	260	140	178.34	130	.750	237.7	Numerous bulbs
	4	843	783	.160	320	105	133.75	138	1.078	124.07	Numerous bulbs
	5	1.147	787	.360	720	21	26.75	127	.4407	60.70	Numerous bulbs
	6	1.097	887	.210	420	66.5	84.71	130	.7737	109.49	Numerous bulbs

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